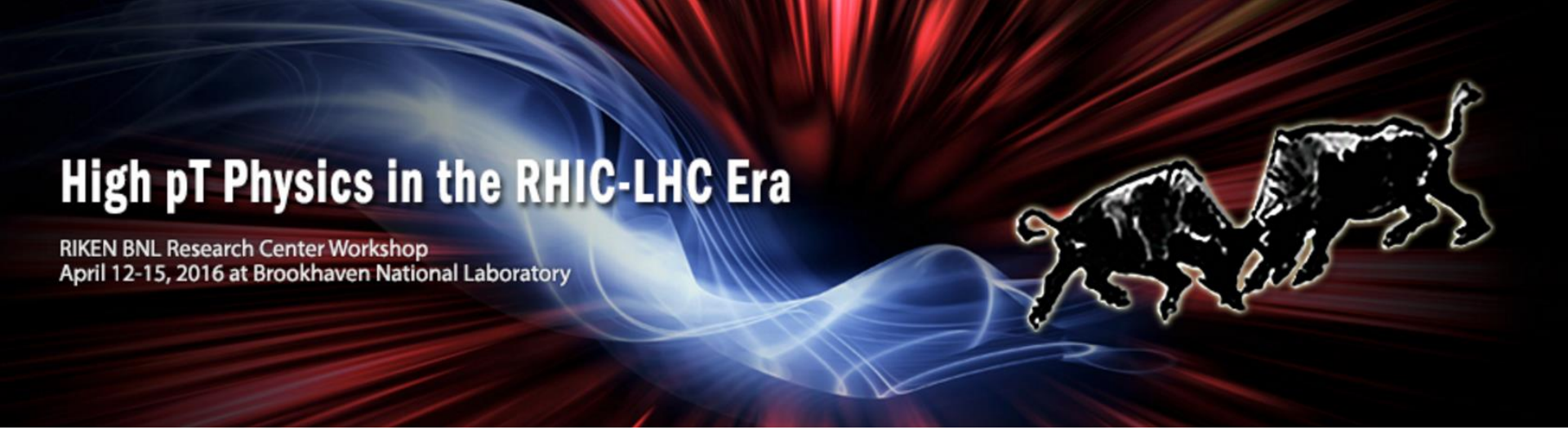


"High-p_T" measurements from the RHIC Beam Energy Scan

Stephen Horvat

Yale University

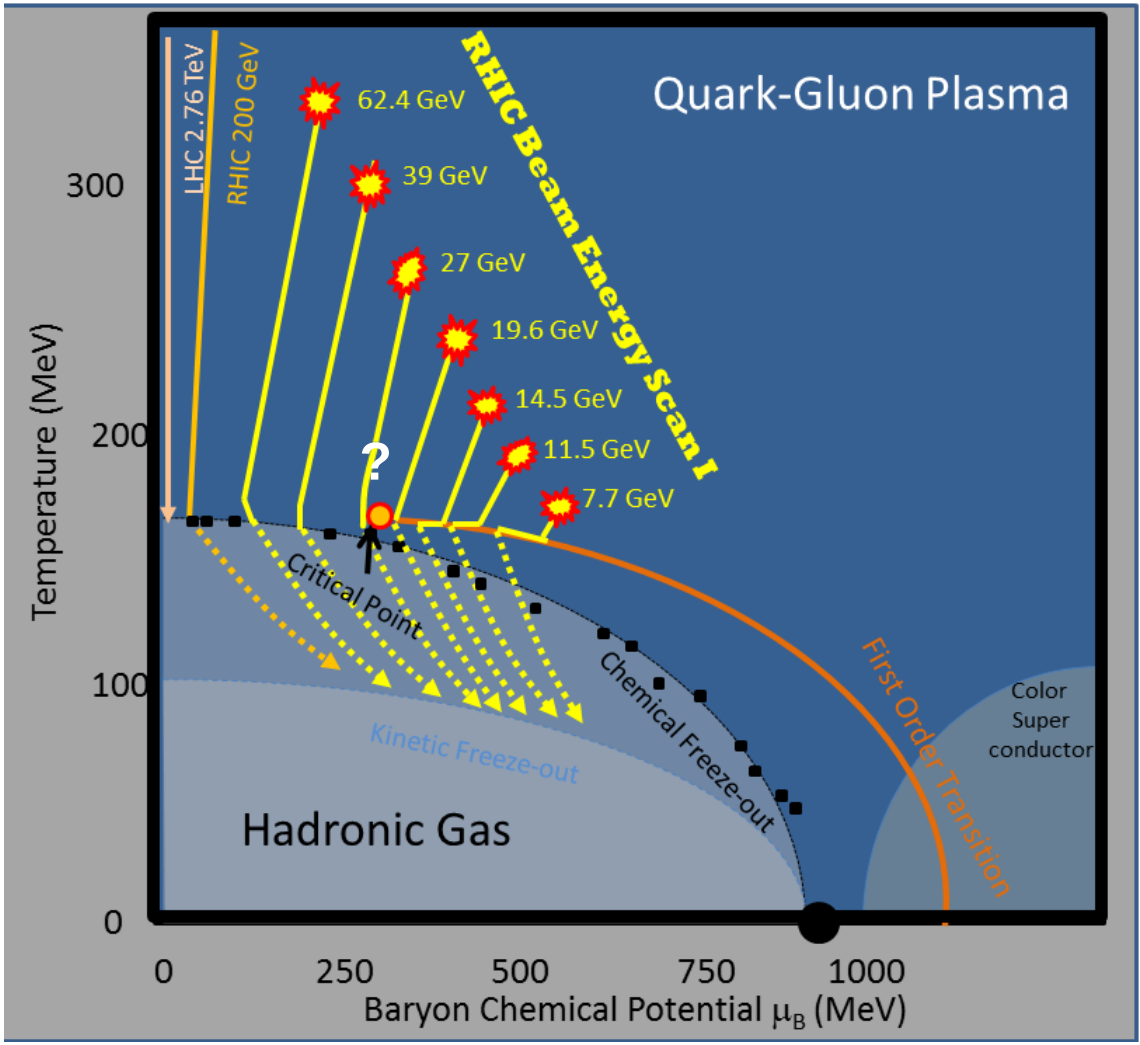
U.S. DEPARTMENT OF ENERGY | Office of Science

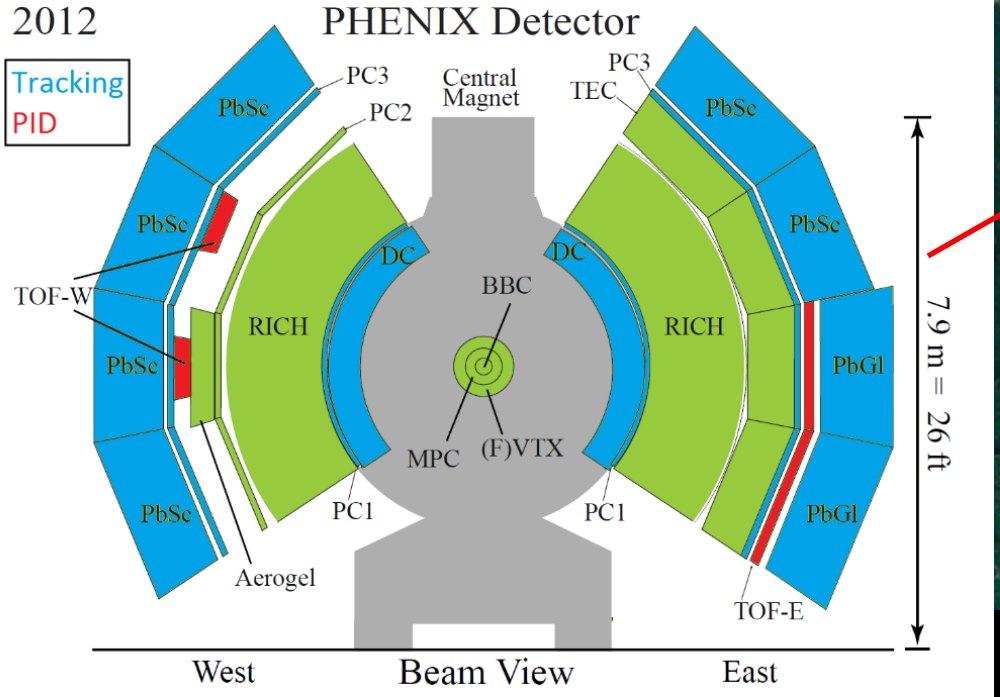
Outline

- Introduction
  - Beam Energy Scan (BES)
  - Detectors/Data
  - High-p_T motivation
- Fractional energy loss (S_{loss})
- Nuclear modification factor (R_{CP})
  - Charged hadron
  - Identified
- N_{part} scaled high p_T yield (Y)
- Other (not “high-p_T”) results from BES I
- BES II
- Summary

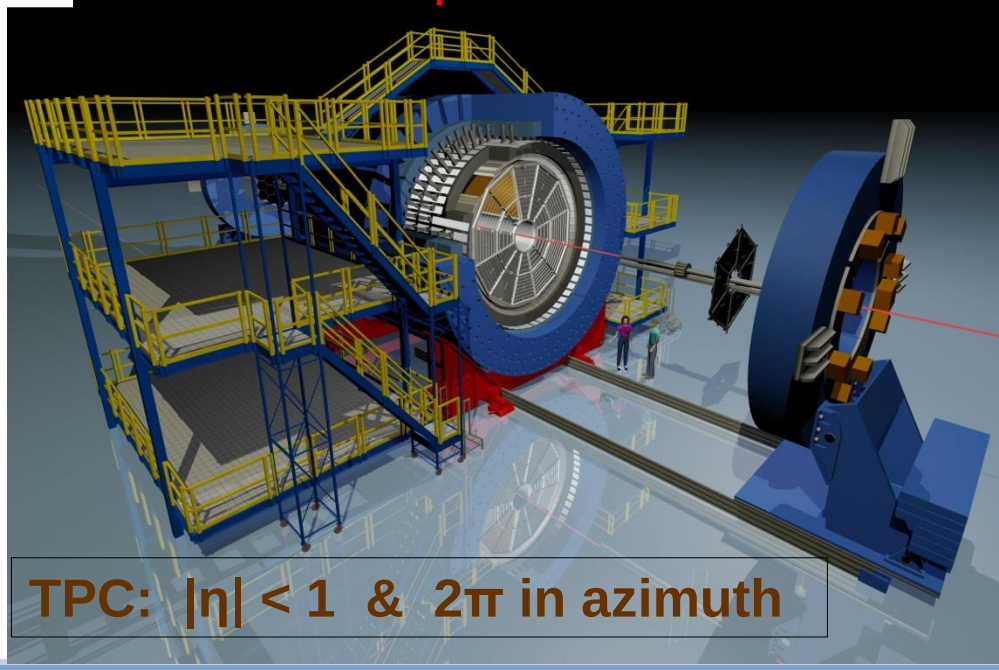
Beam Energy Scan

- At what energy do key QGP formation signatures turn off?
- Is there a critical point and if so where?
- Is there evidence for a first order phase transition?





The Solenoidal Tracker At RHIC (STAR)



Detectors for RHIC BES I

Data

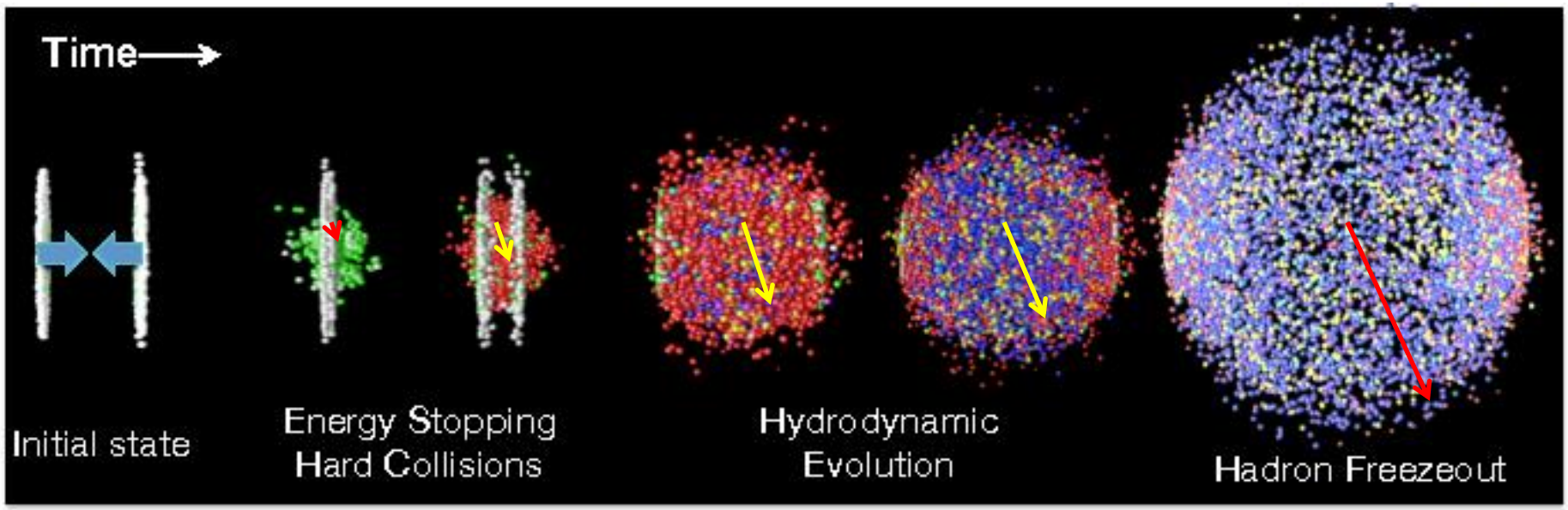
- These data are from phase 1 of the BES at RHIC
- In 2018-2019 phase 2 of the BES will provide additional statistics and energies in Au+Au for $\sqrt{s_{NN}} < 20\text{GeV}$

Au+Au

$\sqrt{s_{NN}}$(GeV)	Year
7.7	2010
11.5	2010
14.5	2014
19.6	2011
27	2011
39	2010
62.4	2010
200	several

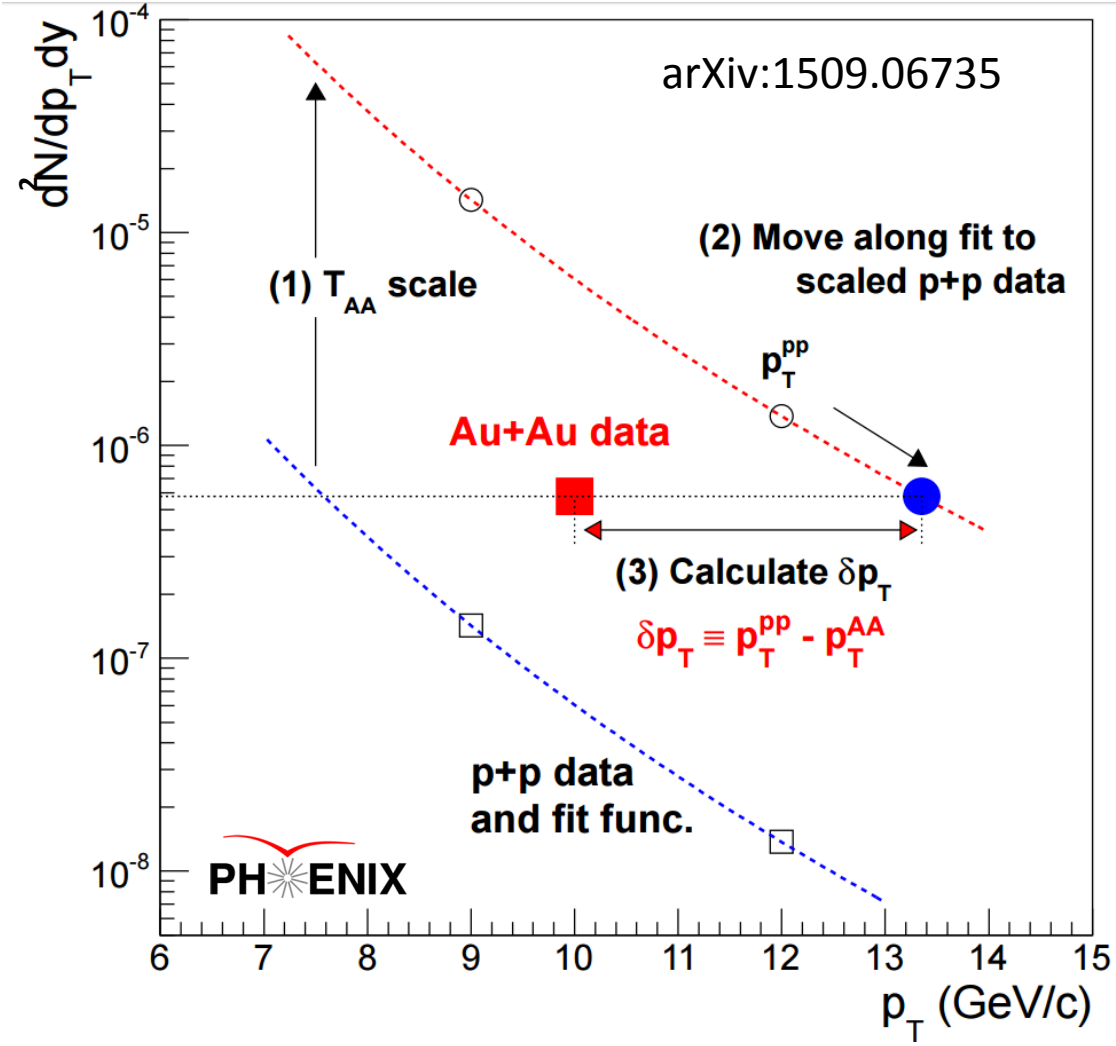
High-p_T motivation

T.C. Awes, ORNL XXVIII



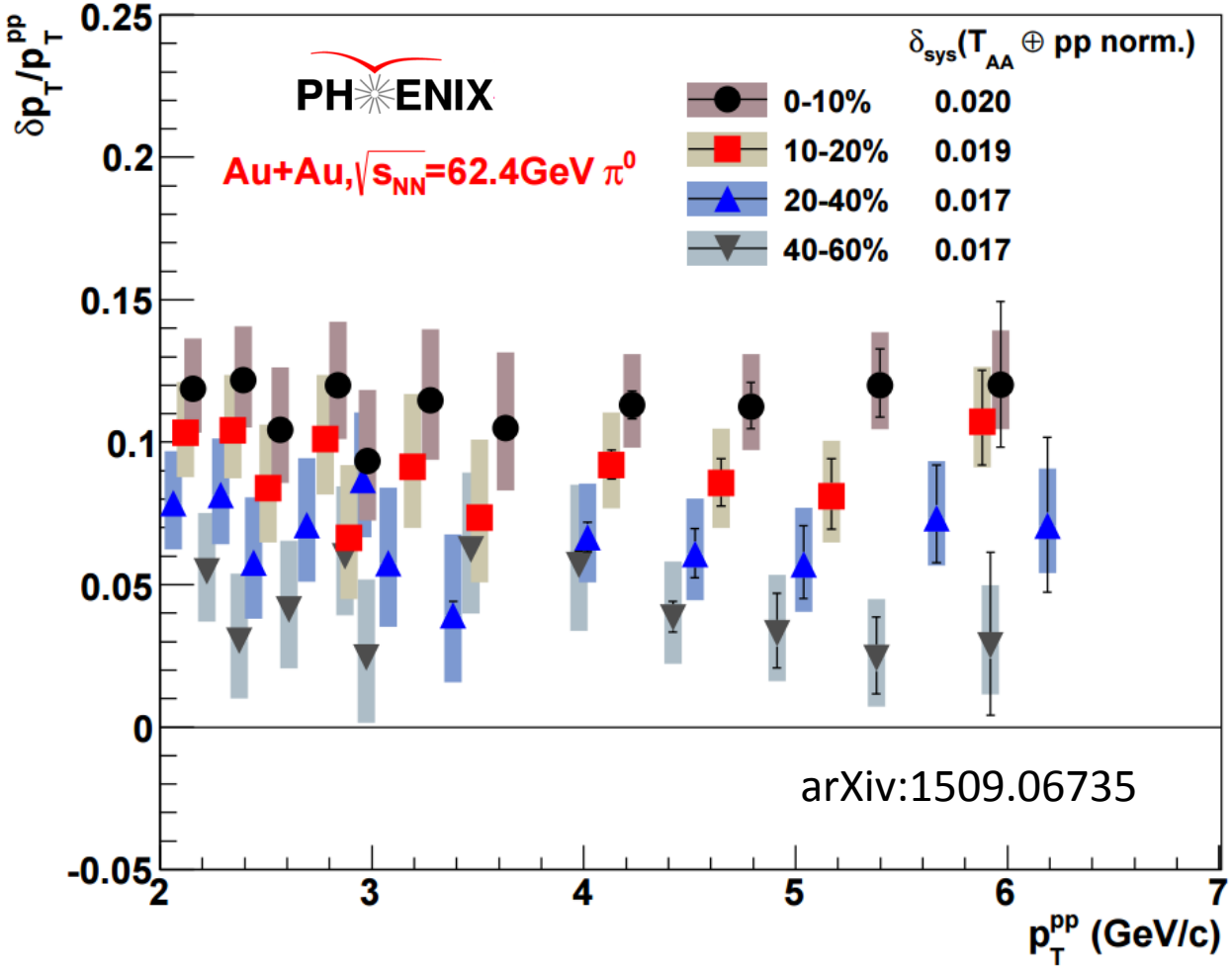
nPDF	hard scattering	partonic E-loss	fragmentation
	Cronin-like enhancement	radial flow	coalescence
	nuclear E-loss		hadronic E-loss

$S_{loss}=\delta p_T/p_T^{pp}$



- Direct relationship to partonic energy loss
- Same R_{AA} means different energy loss if spectra are more steeply falling

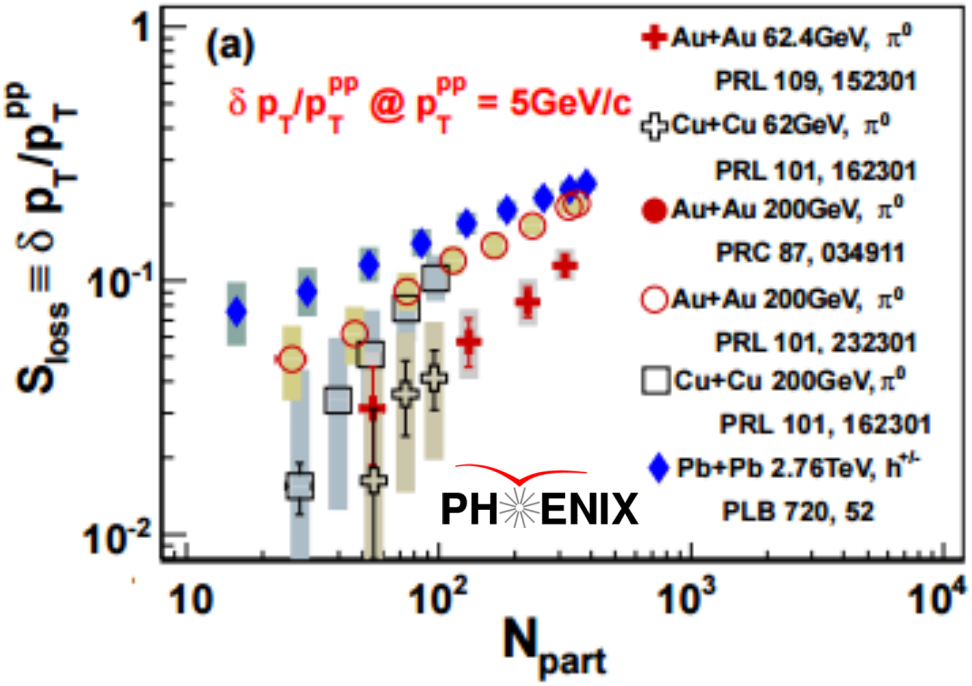
S_{loss}



- Nearly constant fractional energy loss for each centrality
- Larger fractional energy loss for more central collisions

S_{loss}

arXiv:1509.06735

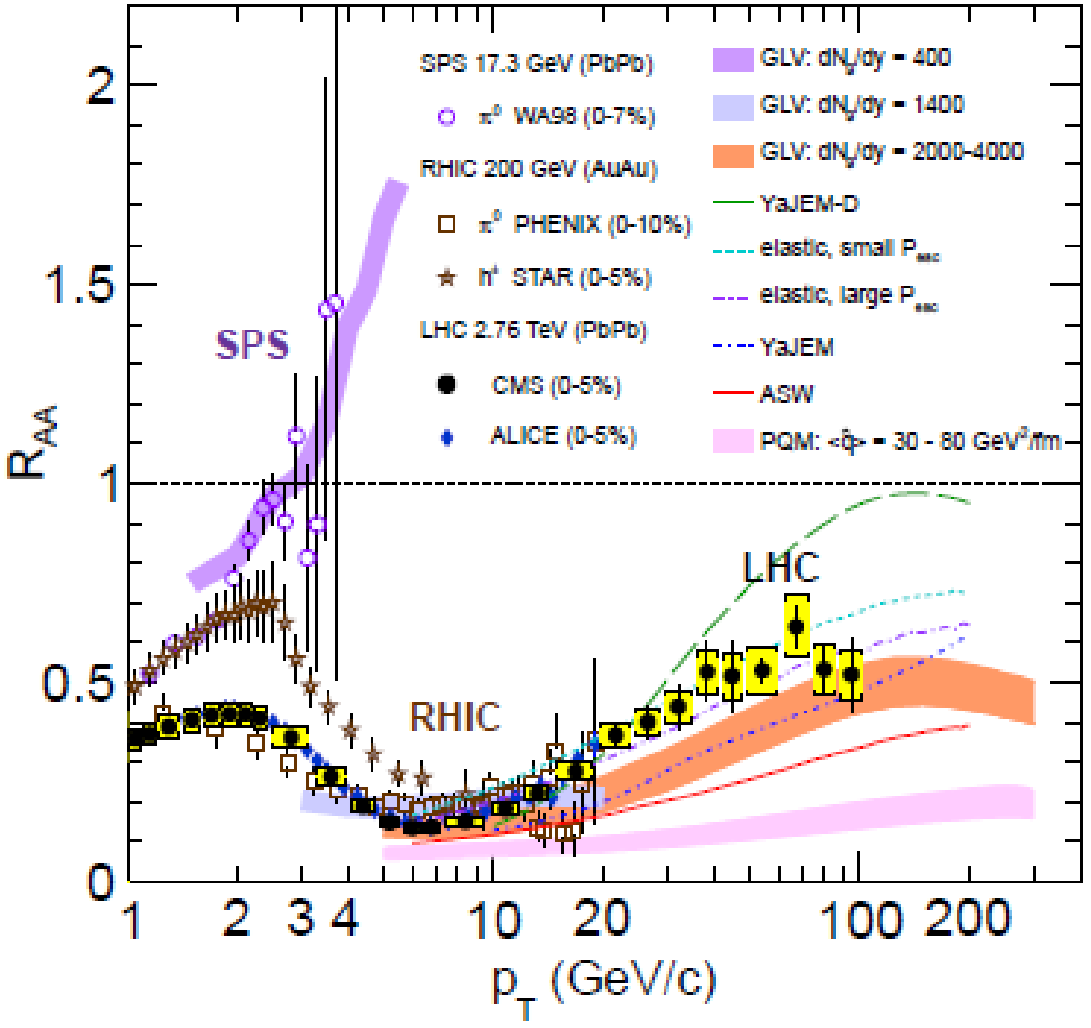


- Increasing fractional energy loss with N_{part} and collision energy

State of world's R_{AA}

- R_{CP} is used in the BES when there is not a p+p reference

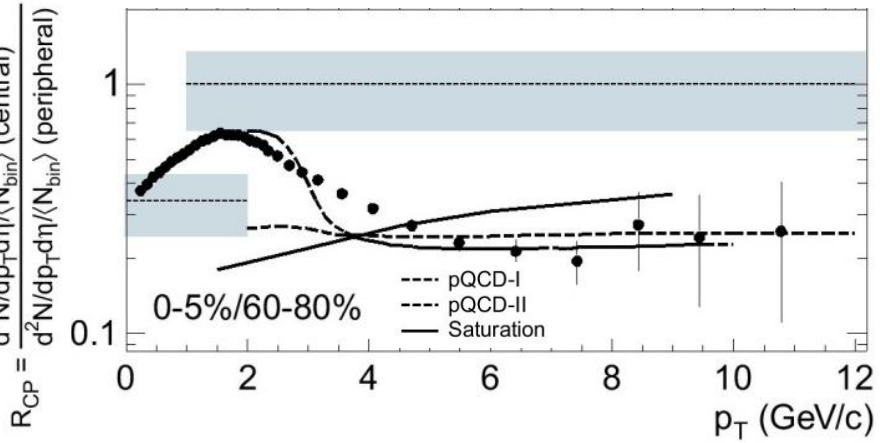
CMS: Eur. Phys. J. C **72** (2012) 1945



Suppression of high p_T

$$R_{CP} = \frac{\text{  }}{\text{  }}$$

Au+Au 200



STAR: Phys. Rev. Lett. 91, 172302 (2003)

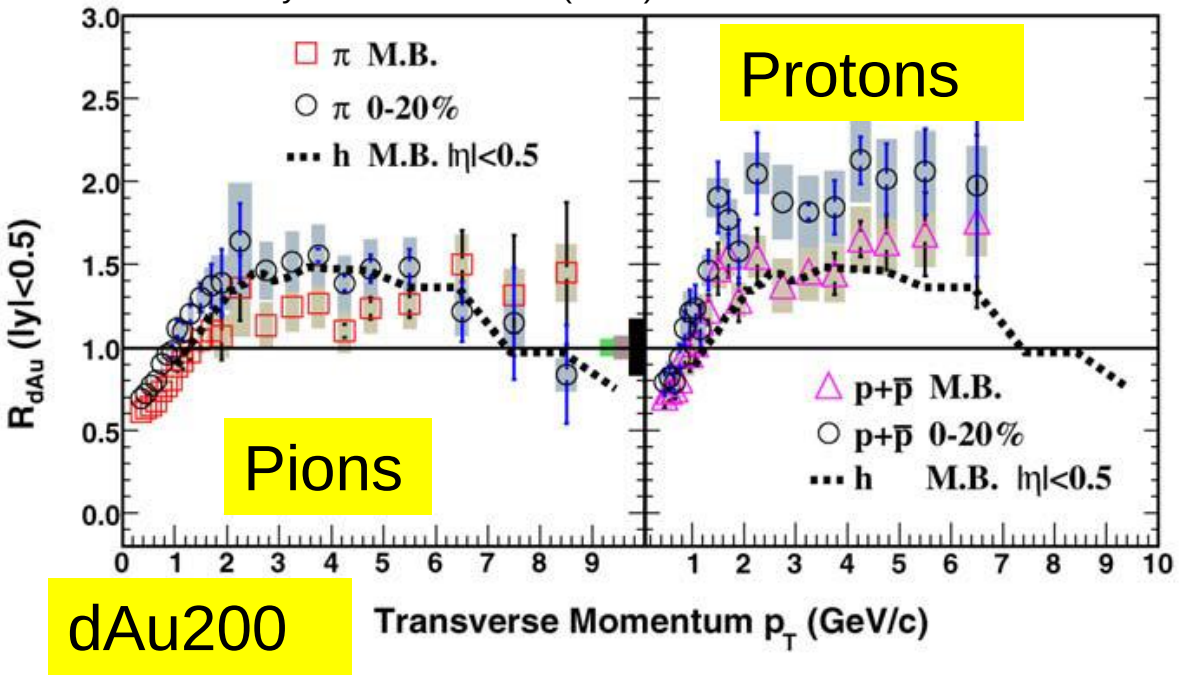
high p_T charged hadrons are suppressed at $\sqrt{s_{NN}}$ = 200GeV

'Suppression' ≡ $R_{CP} < 1$

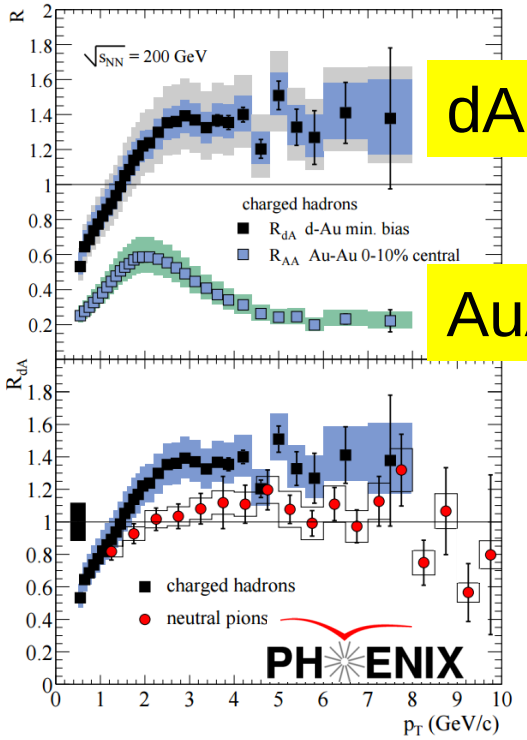
'Quenching' ≡ loss of energy for high momentum particles

d+Au for Cold Nuclear Matter (CNM)

STAR: Physics Letters B 637 (2006) 161–169



arXiv:nucl-ex/0306021

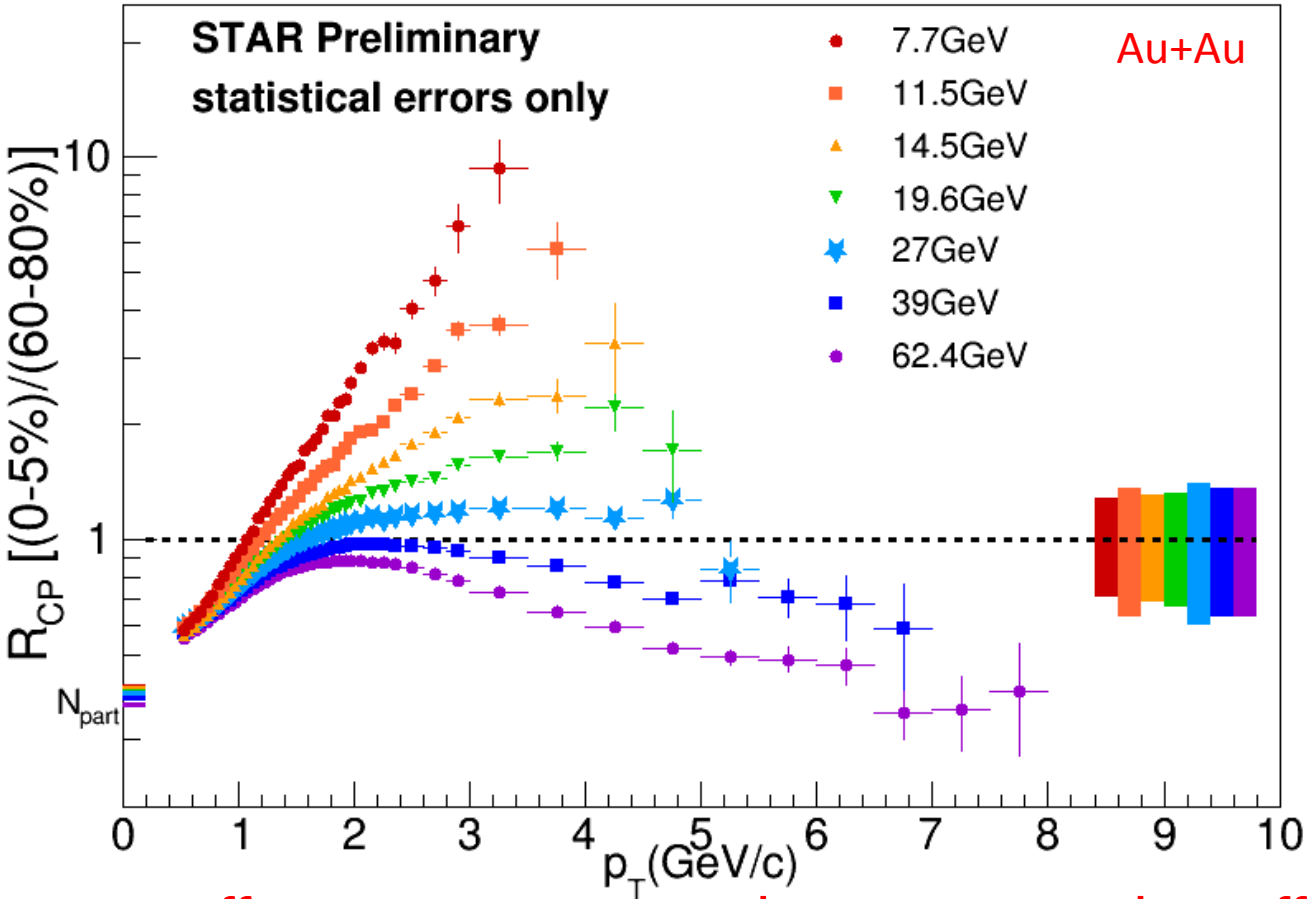


The ‘Cronin Effect’ is the experimentally observed enhancement of spectra in p+A collisions relative to a p+p reference

PRL 68, 452 (1992) Straub

BES I Charged Hadron R_{CP}

S. Horvat, QM2015



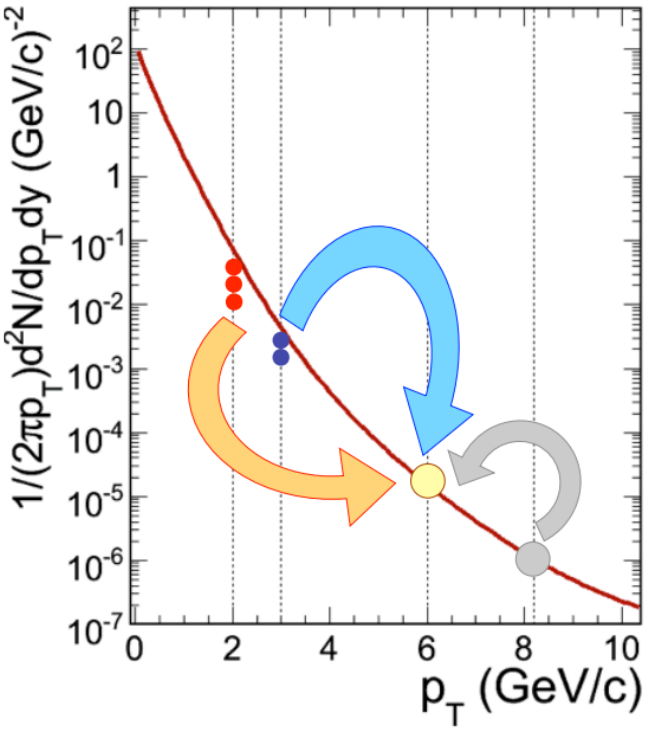
- Enhancement effects compete against suppression effects concealing the turn off of QGP formation at low $\sqrt{s_{NN}}$

An incomplete list of possible Enhancement Effects

- Anti-Shadowing
- k_T smearing
- Radial Flow
- Coalescence
- …

Coalescence vs Fragmentation

Quark (parton) coalescence



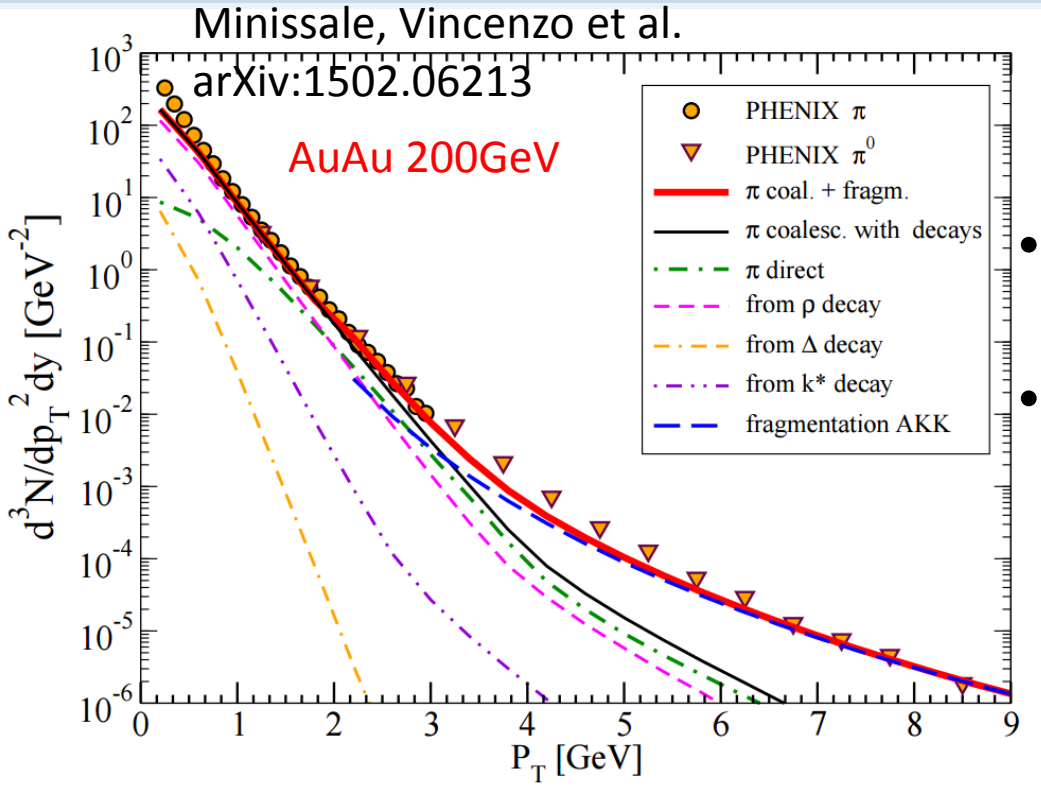
*D. Molnar and S. A. Voloshin, **PRL91**, 092301 (2003), R. C. Hwa and C. B. Yang, **PRC66**, 025205 (2002), V. Greco et al, **PRL90**, 202302 (2003), R. J. Fries et al, **PRL90**, 202303 (2003), ...*

- Hadron productions by quark coalescence picture
- Specific scaling pattern for meson and baryon v_2

Hiroshi Masui HHIQCD2015

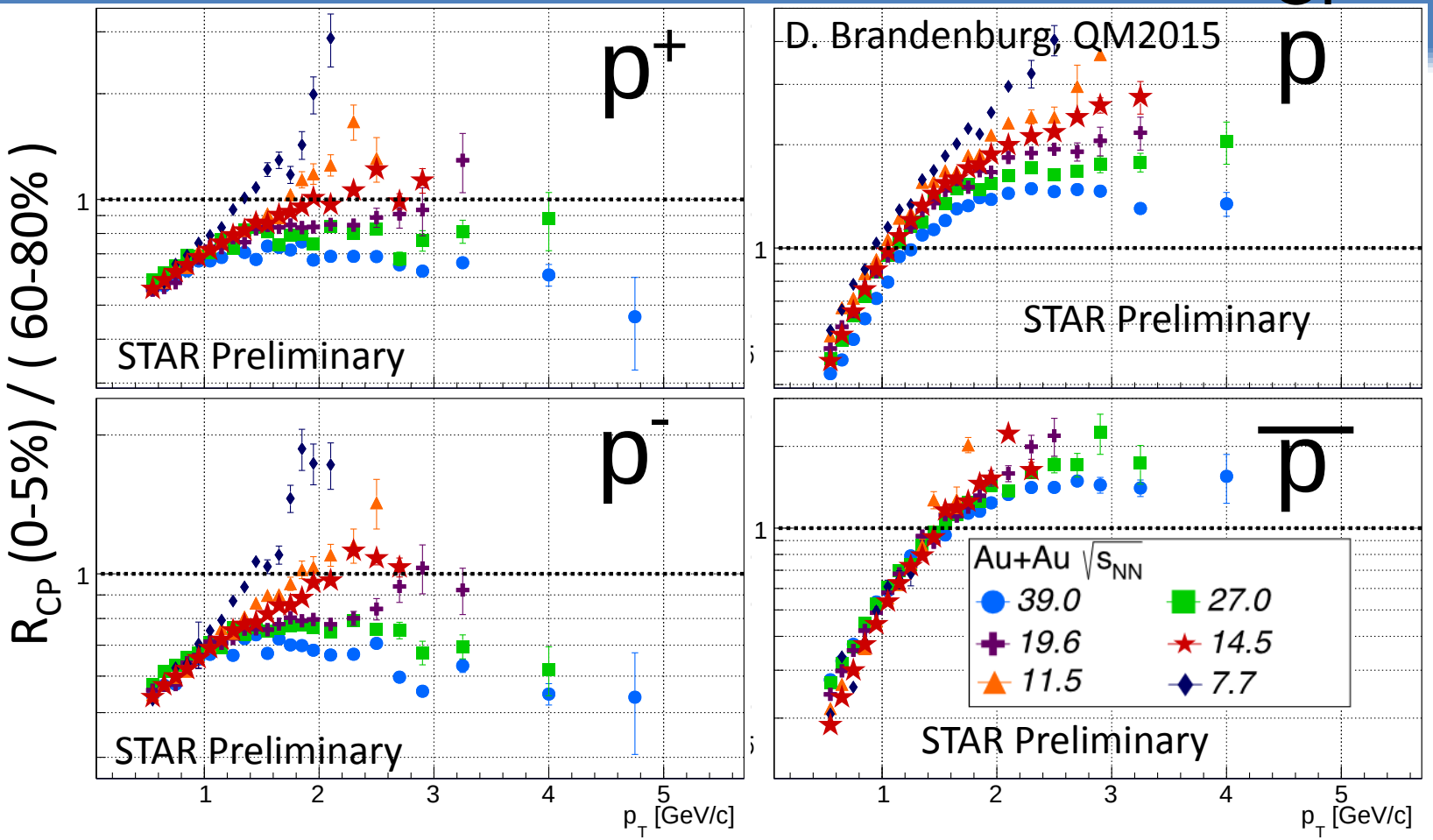
H. Masui / Univ. of Tsukuba *12 /31*

Coalescence vs Fragmentation



- coal. + frag does well at top RHIC and LHC energies
- Can particles in the BES reach momenta where a significant fraction come from fragmentation?

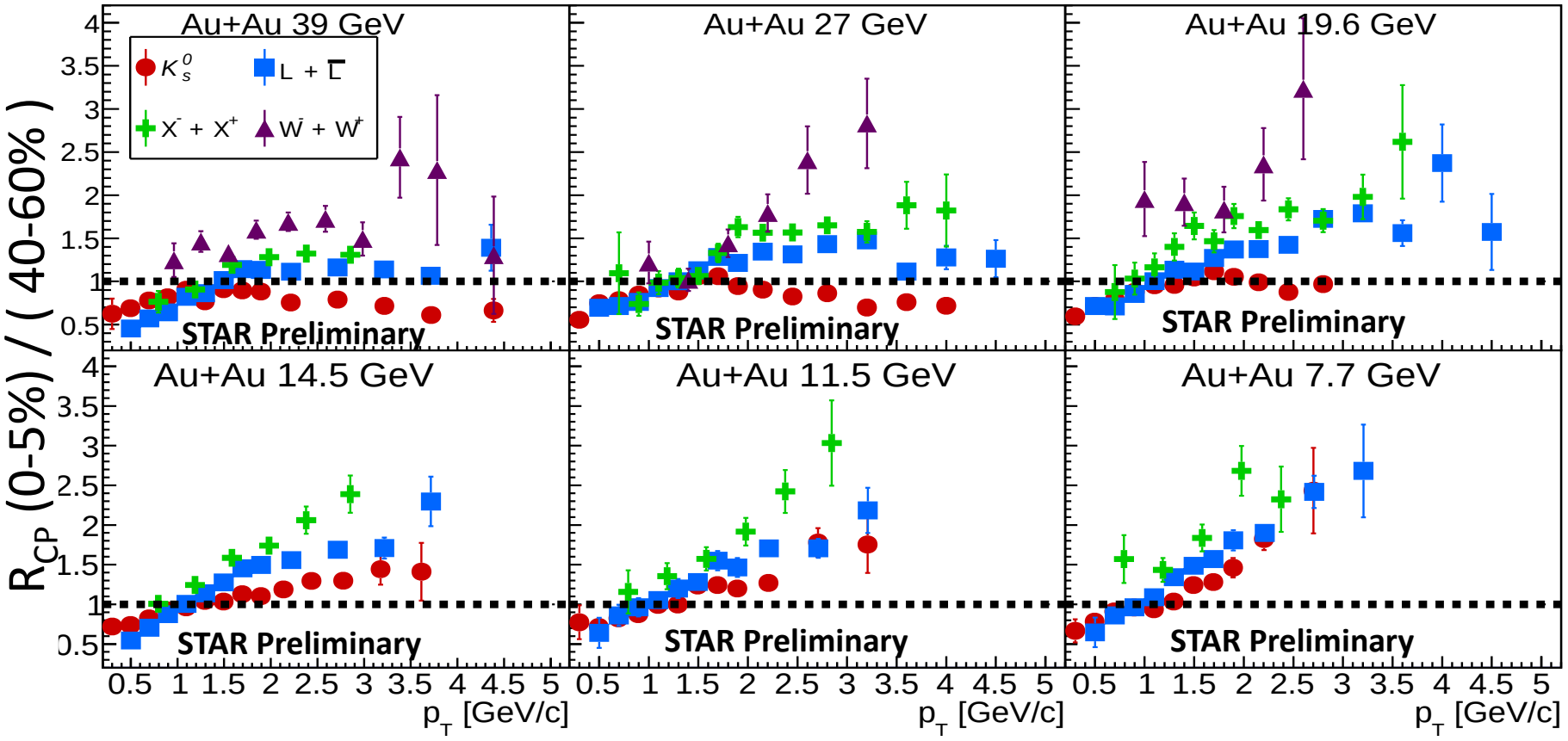
BES I Pion, Proton R_{CP}



- Pions are less modified by coalescence and other enhancement effects than protons

→ better QGP probe?

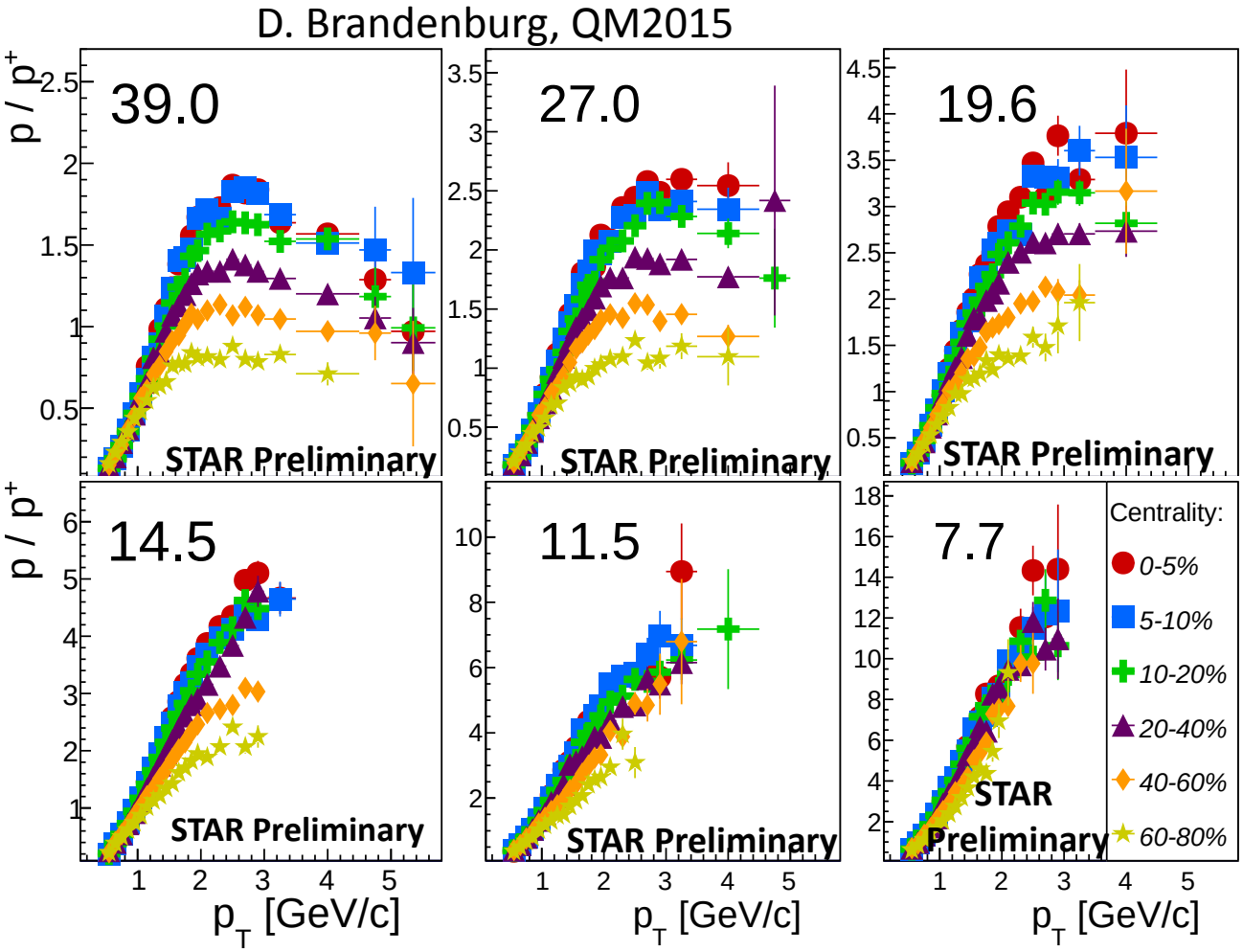
BES I Strange Hadron R_{CP}



- R_{CP} particle type dependence becomes less significant as energy is reduced
- Strange hadrons look similar to protons and pions dependence on baryon/meson

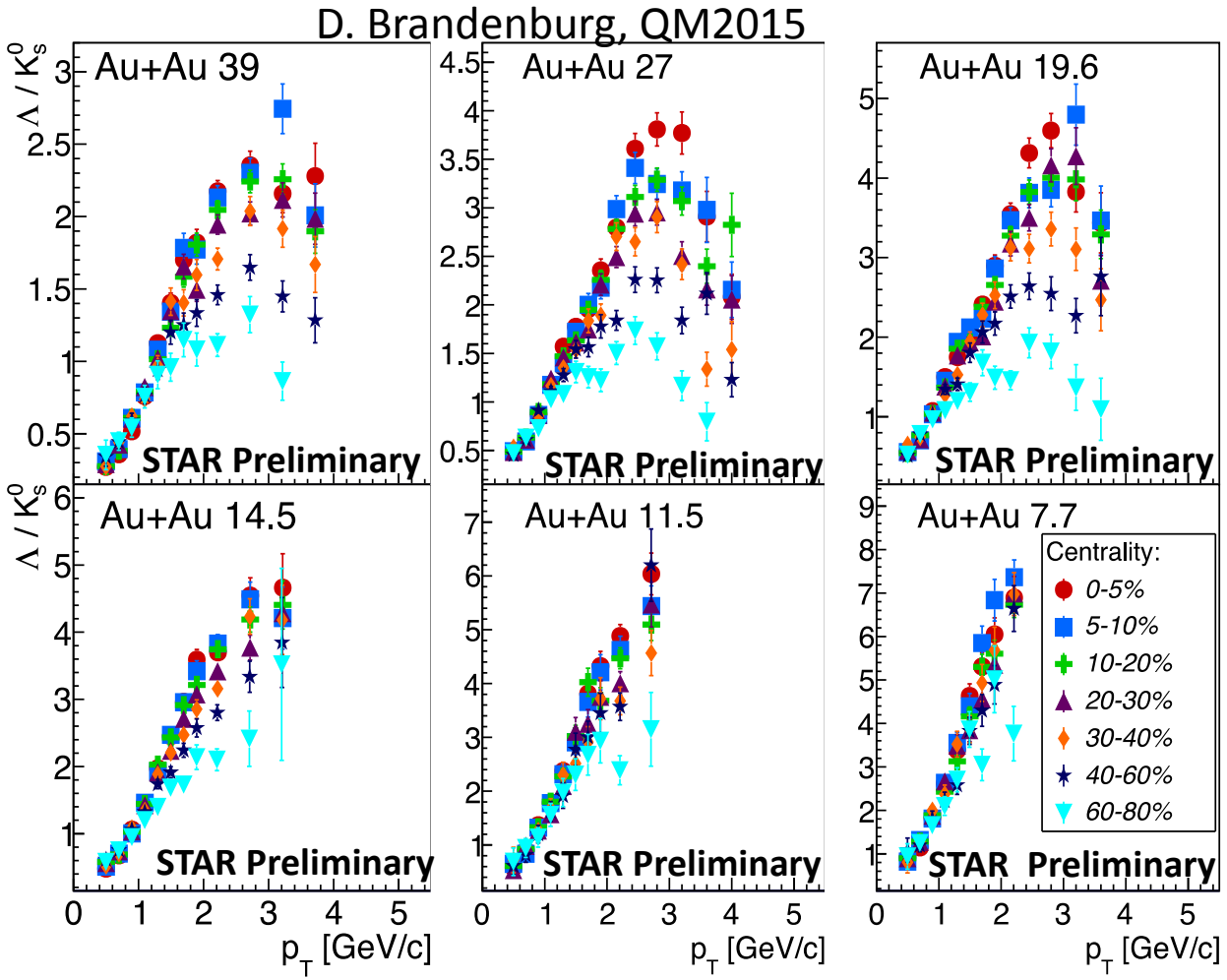
BES I p/π^+

- Centrality dependence decreases with energy



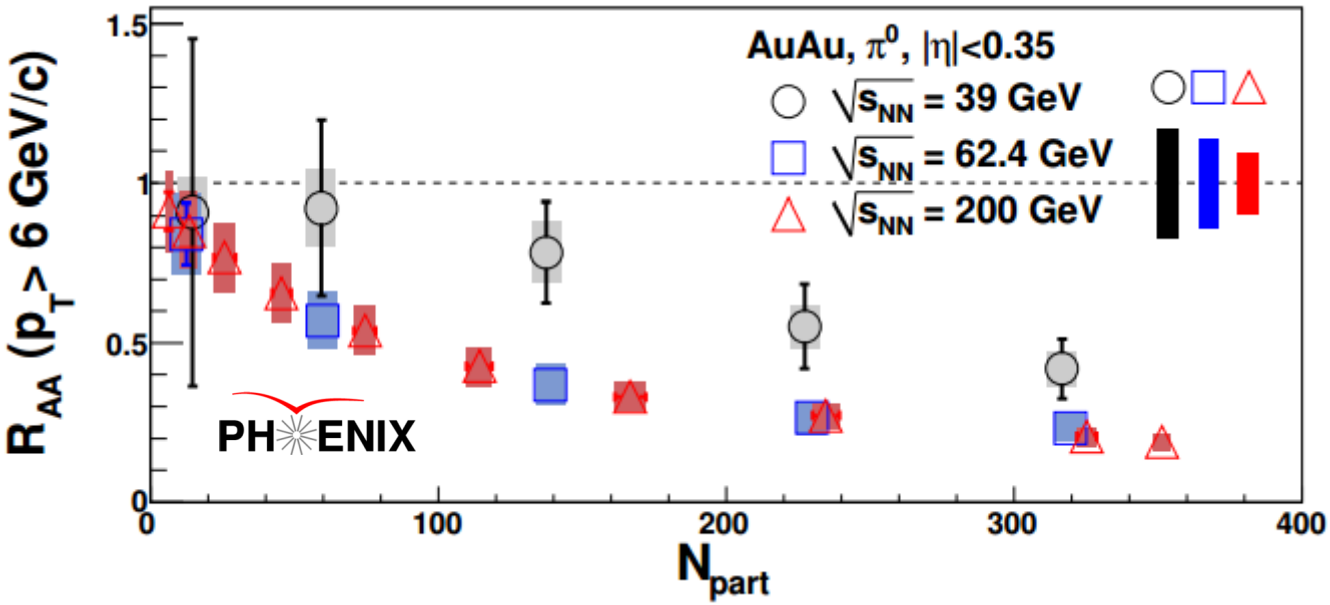
BES I Λ/K_s^0

- Centrality dependence decreases with energy



π^0 R_{AA} (N_{part})

arXiv:1204.1526



- High-p_T R_{AA} decreases with centrality

→ Suppression effects increase faster than enhancement effects with increasing N_{part}

- There is a common factor from the p+p data that does not effect the shape of these distributions

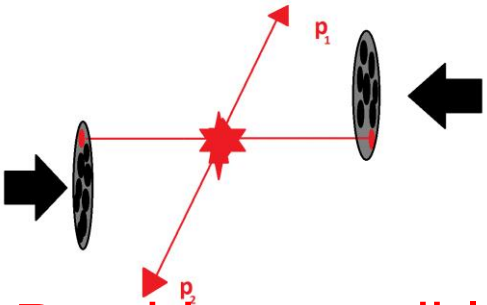
$Y(N_{part})$

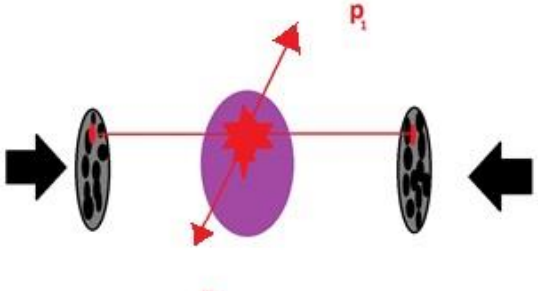
- $Y(N_{part})$ takes a projection at high-p_T of the numerator from R_{CP} and investigates its centrality dependence
- This is preferable to $R_{CP}(N_{part})$ since the peripheral spectra would be a common factor and with large error bars

Au + Au
Peripheral

$$Y(N_{part}) = \left(\frac{d^2N}{\langle N_{coll}\rangle dp_T d\eta}\right)_{high-p_T\ bin}$$

Au + Au
Central

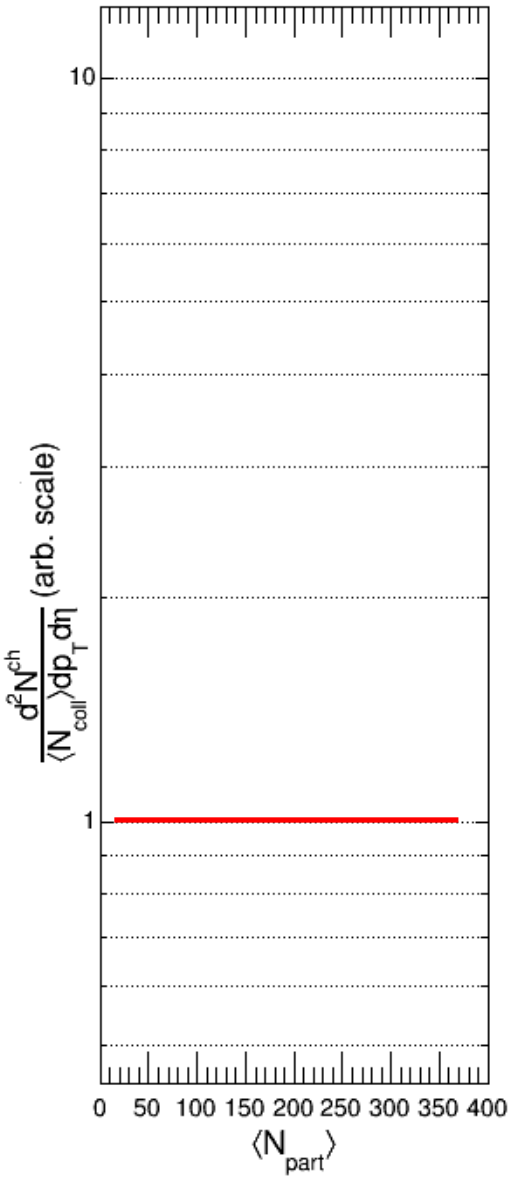




- Provides possible evidence for where a QGP **is** formed

N_{coll} ≡ number of binary collisions (from Glauber MC)

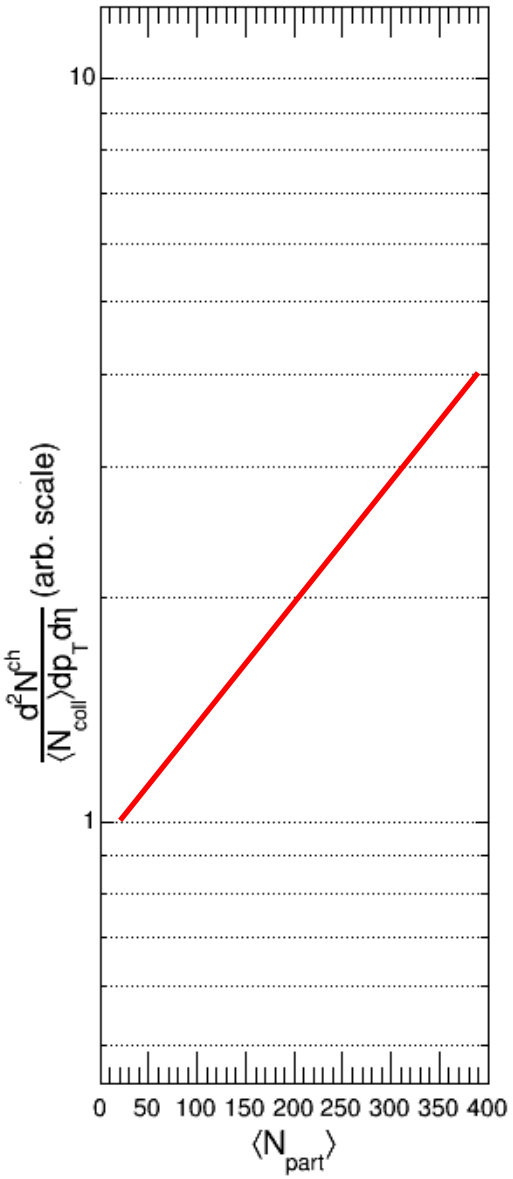
$Y(N_{part})$



- If the "high-p_T" region scales with N_{coll} such that we can consider the Au+Au collision to be a linear superposition of p+p-like collisions then we would expect $Y(N_{part})$ to be flat at unity

$$Y(N_{part}) = \left(\frac{d^2N}{N_{coll} dp_T d\eta}\right)_{high-p_T\ bin}$$

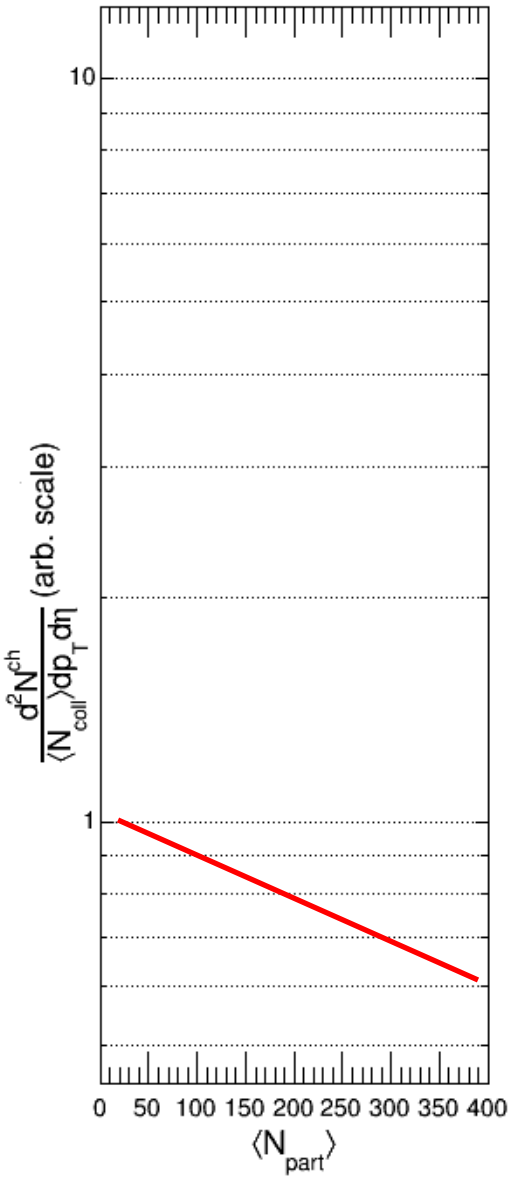
$Y(N_{part})$



- If there are enhancement effects that grow stronger as you go more central then you would expect $Y(N_{part})$ to increase with N_{part}
  - Radial Flow
  - Coalescence
  - …

$$Y(N_{part}) = \left(\frac{d^2N}{N_{coll} dp_T d\eta}\right)_{high-p_T\ bin}$$

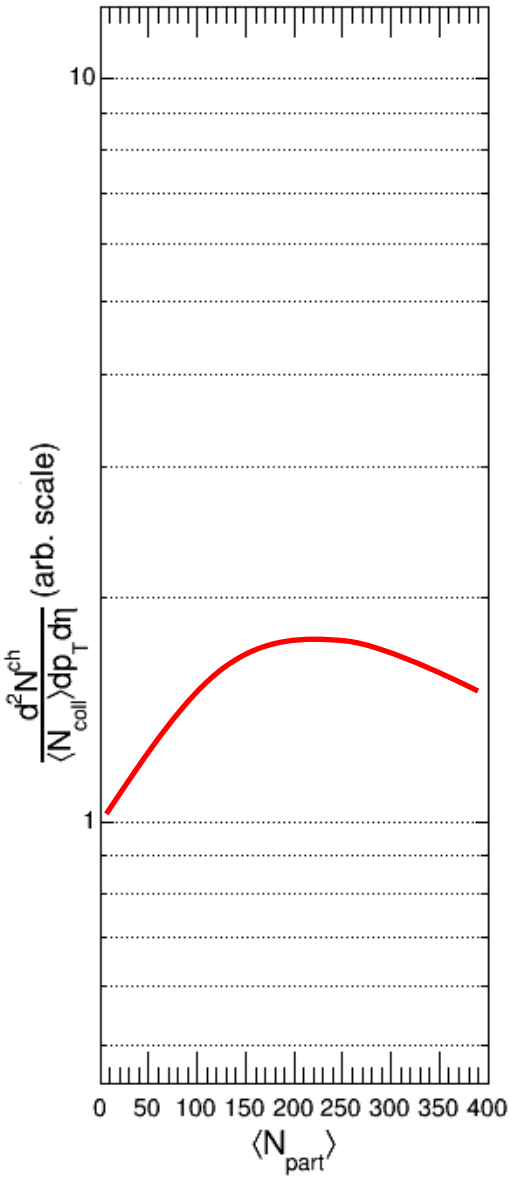
$Y(N_{part})$



- Suppression that grows stronger as you go more central would give:

$$Y(N_{part}) = \left(\frac{d^2N}{N_{coll} dp_T d\eta}\right)_{high-p_T\ bin}$$

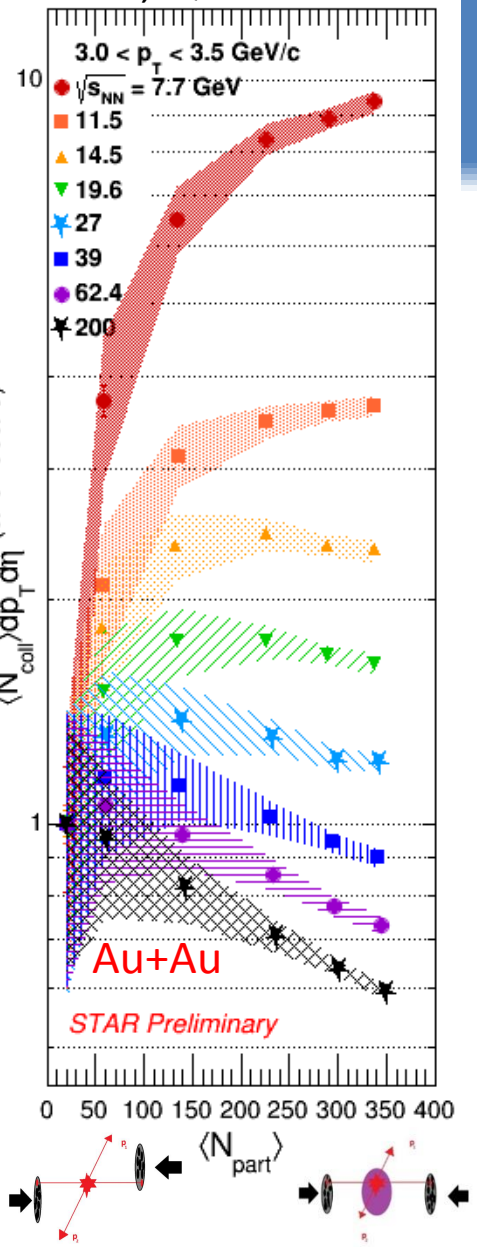
$Y(N_{part})$



- Enhancement and suppression effects compete against each other
- $Y(N_{part})$ measures the net change in these as a function of centrality
- If enhancement grows faster initially but suppression effects become more dominant as you go more central (or enhancement effects become weaker) then there will be a turnover in $Y(N_{part})$
- The suppression is measured relative to a centrality that contains enhancement effects (Cronin, Radial Flow, etc.) rather than a p+p-like system

$$Y(N_{part}) = \left(\frac{d^2N}{N_{coll} dp_T d\eta}\right)_{high-p_T\ bin}$$

S. Horvat, QM2015

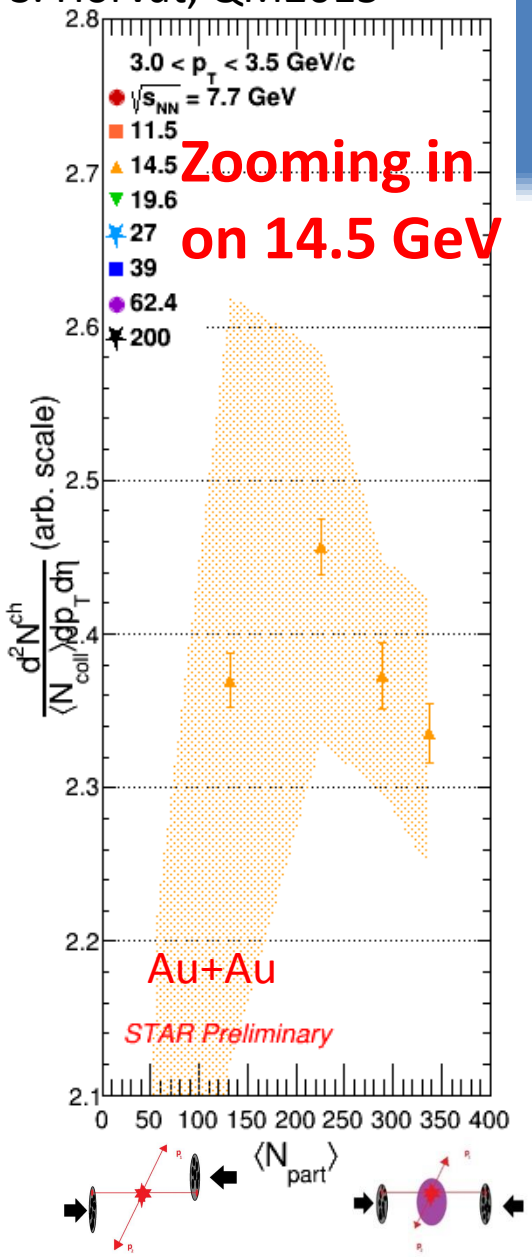


$Y(N_{part})$ $3.0 < p_T < 3.5$ GeV/c

- Most central data are suppressed (turnover) for $\sqrt{s_{NN}} \geq 14.5$ GeV
  - This does not rule out the formation of a QGP at lower energies than 14.5 GeV
- 7.7 and 11.5 GeV results increase monotonically
- 200 GeV results decrease monotonically

Error bands are correlated uncertainties

S. Horvat, QM2015



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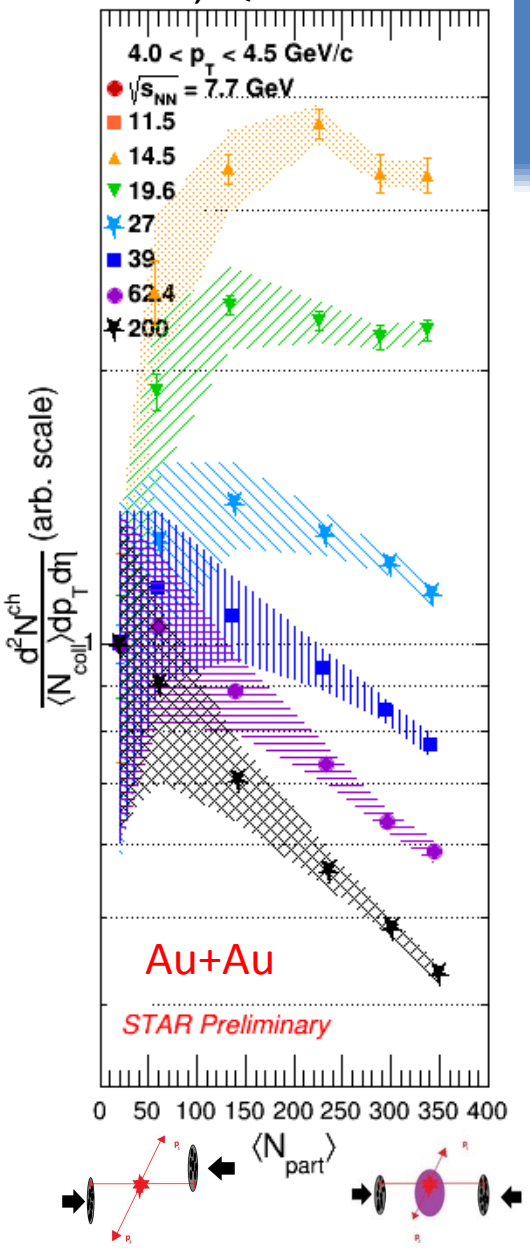
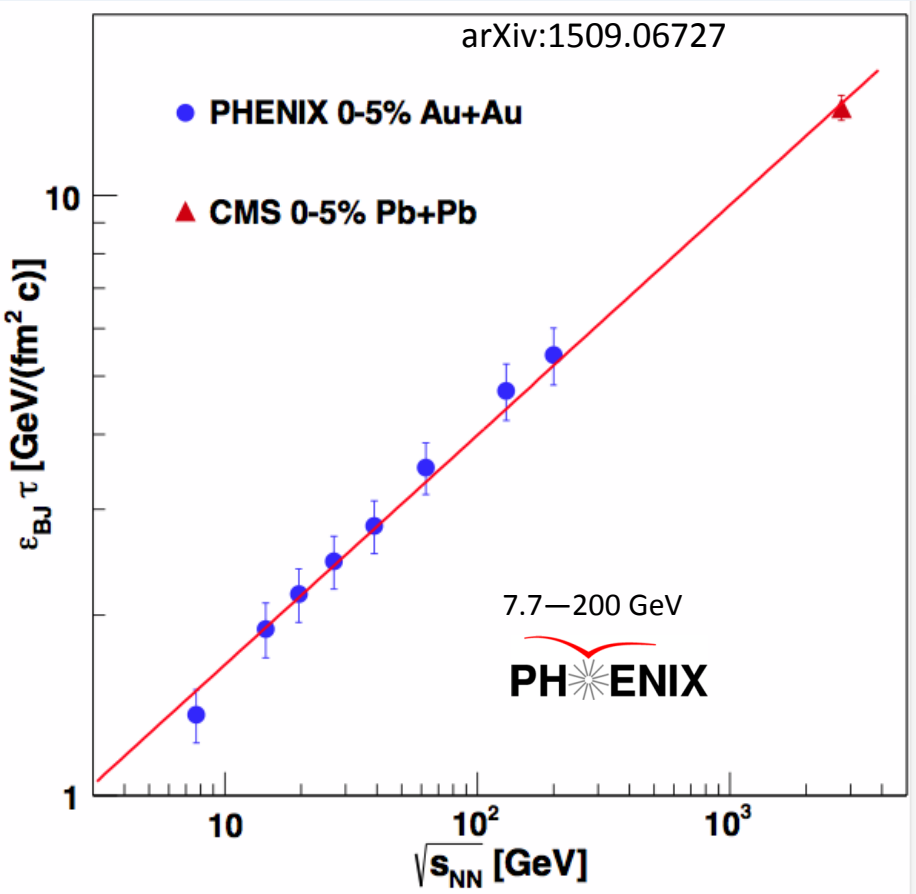


$Y(N_{part})$ $4.0 < p_T < 4.5$ GeV/c

- Most central data are suppressed for $\sqrt{s_{NN}} \geq 14.5$ GeV
- This method is sensitive to charged hadron suppression to a lower energy than previous techniques
- To prove the suppression is due to quenching, possible contributions from hadronic energy loss and impact parameter dependent nPDFs need further investigation
- Looking forward to d+Au at BES energies

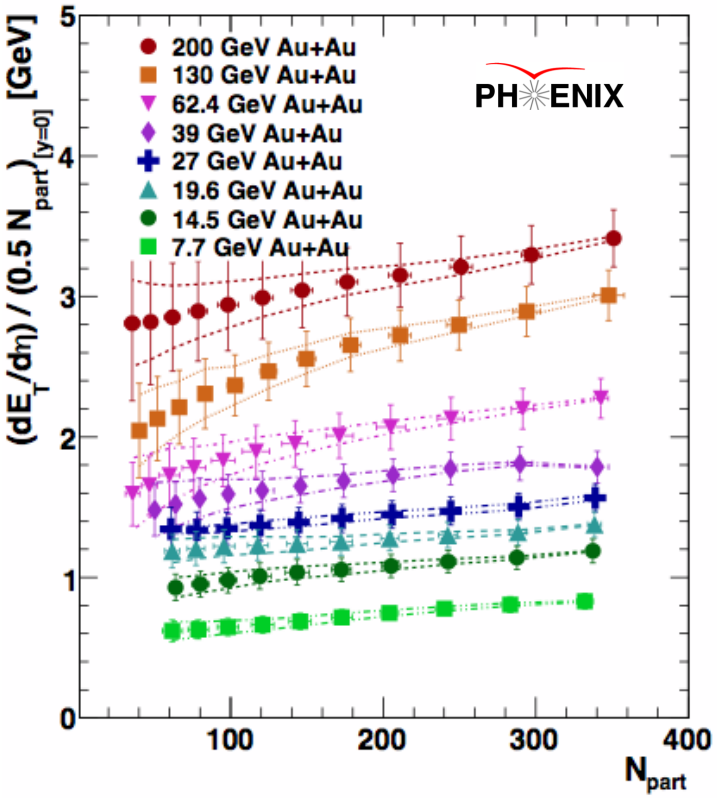
Other BES I Results

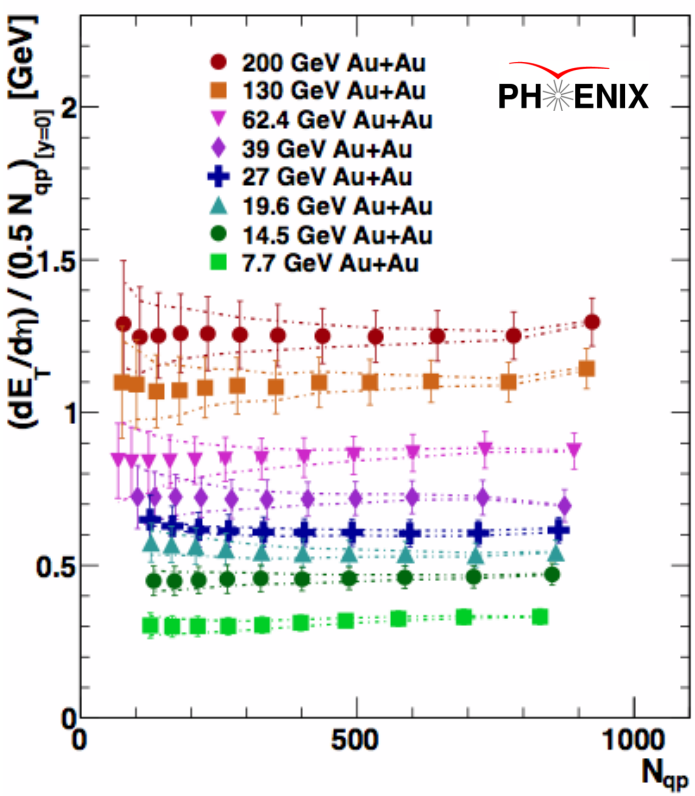


- Bjorken energy density * τ > 1 GeV/(fm^2 c) in central collisions for entire BES
  - ➢ power law scaling

Other BES I Results

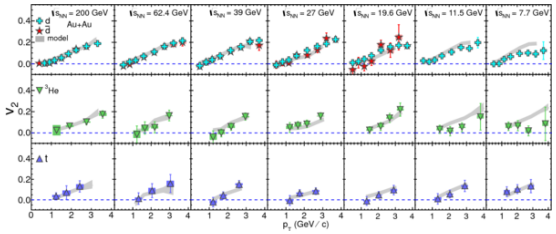
arXiv:1509.06727

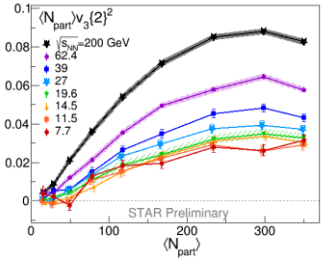


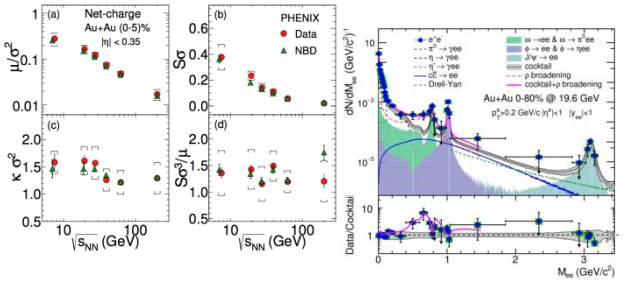


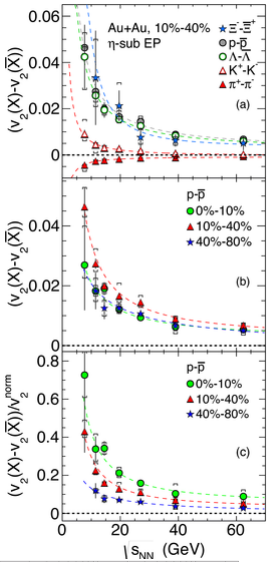
- Transverse energy scales better with quark participants than participating nucleons

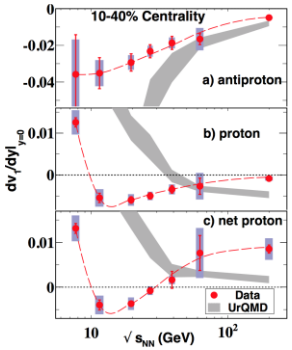
Other BES I Results



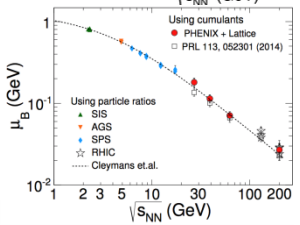


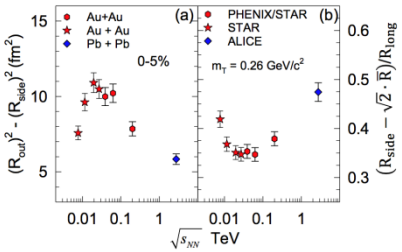


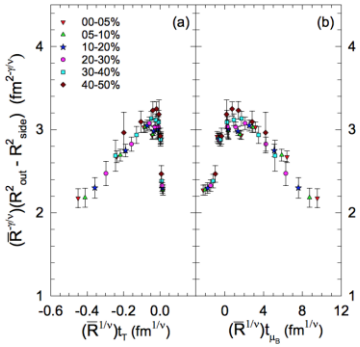


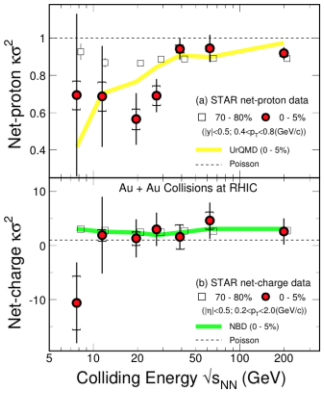


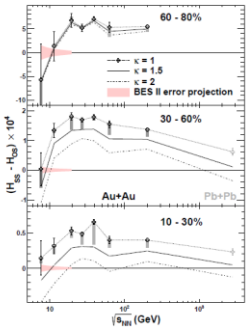
And many more

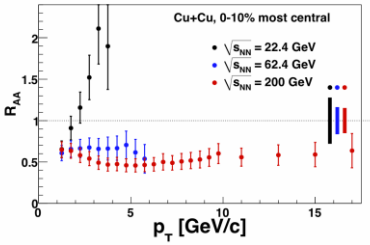






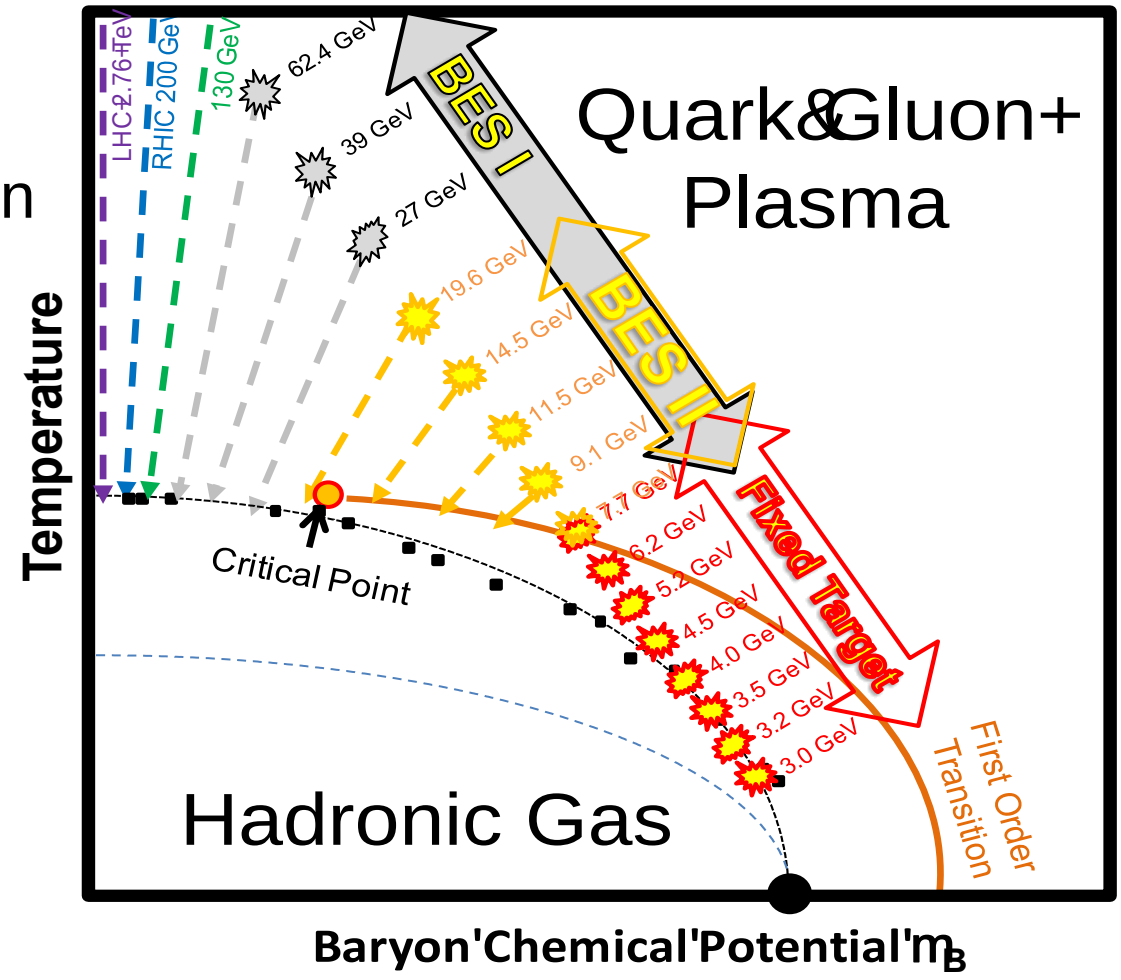






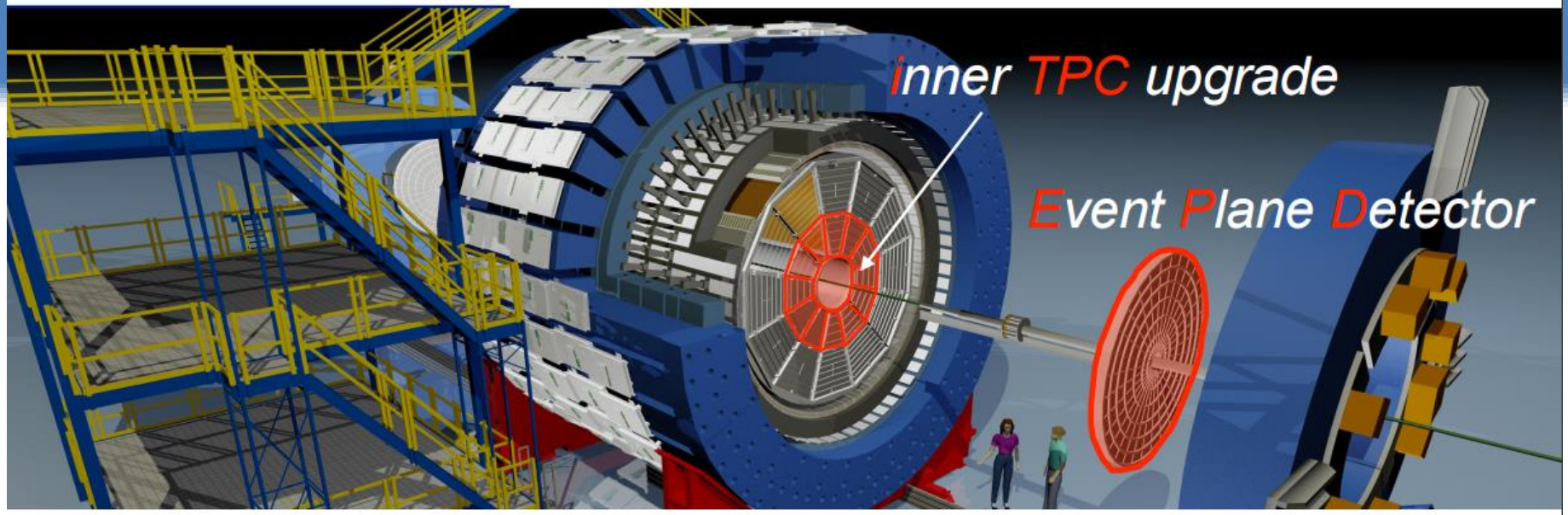
BES II

- Increased RHIC luminosity
- Fixed target installed in STAR



STAR upgrade for BES-II

Hiroshi Masui HHIQCD2015



- Event Plane Detector, $1.8 < |\eta| < 5$
  - Trigger, event plane, centrality
    - suppress backgrounds on flow measurements, independent centrality determination
- inner TPC upgrade
  - increase TPC acceptance from 1 to 1.5 in η
  - improve dE/dx resolution → better PID
- ETOF , improve PID at forward rapidity

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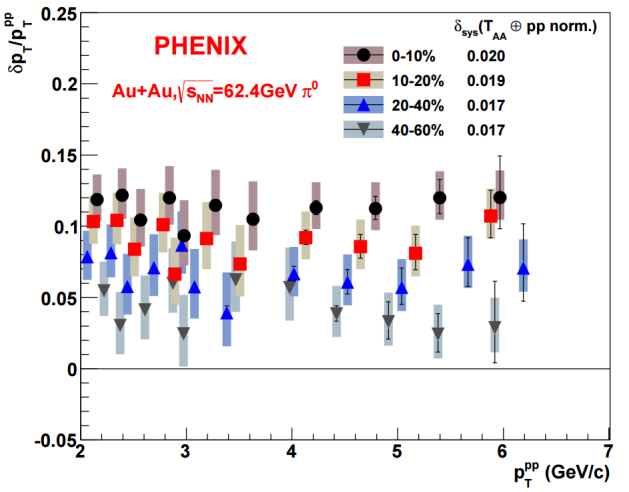
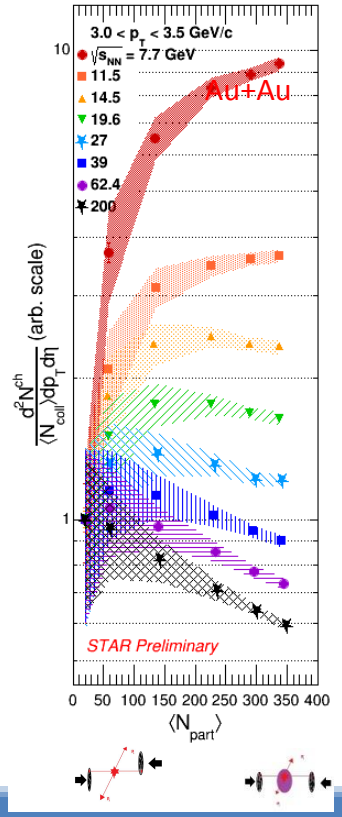
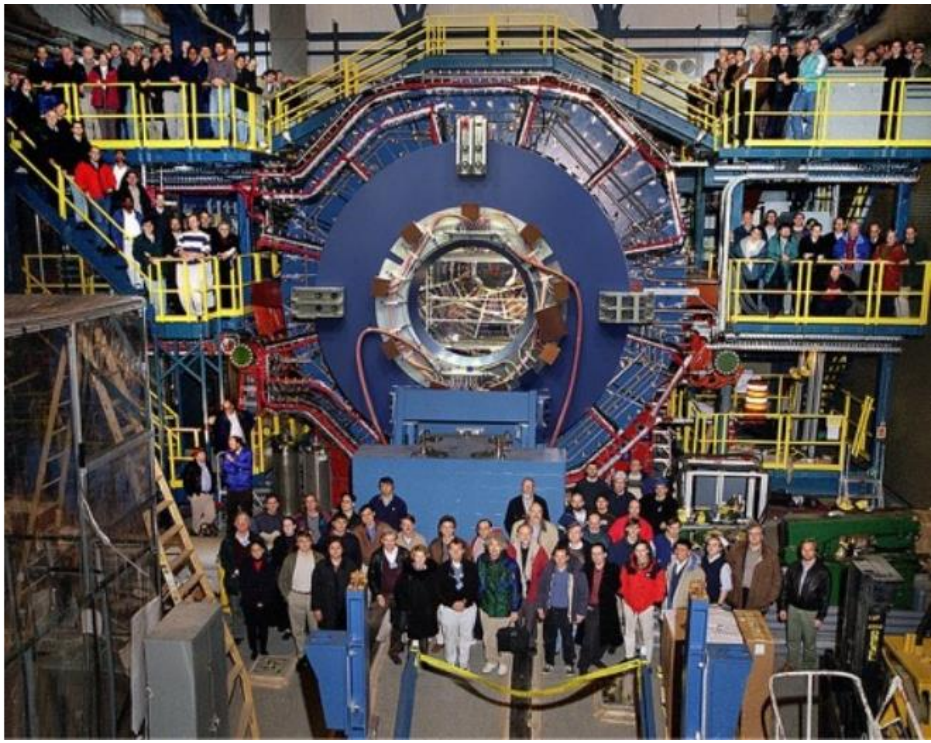
Conclusions

- While there is strong evidence for partonic energy loss at high energy, enhancement effects decrease sensitivity to partonic energy loss at lower energies
- Mesons may be less sensitive to these enhancement effects
- Considering suppression relative to mid-central collisions may help disentangle enhancement and suppression effects
- We are looking forward to BES II

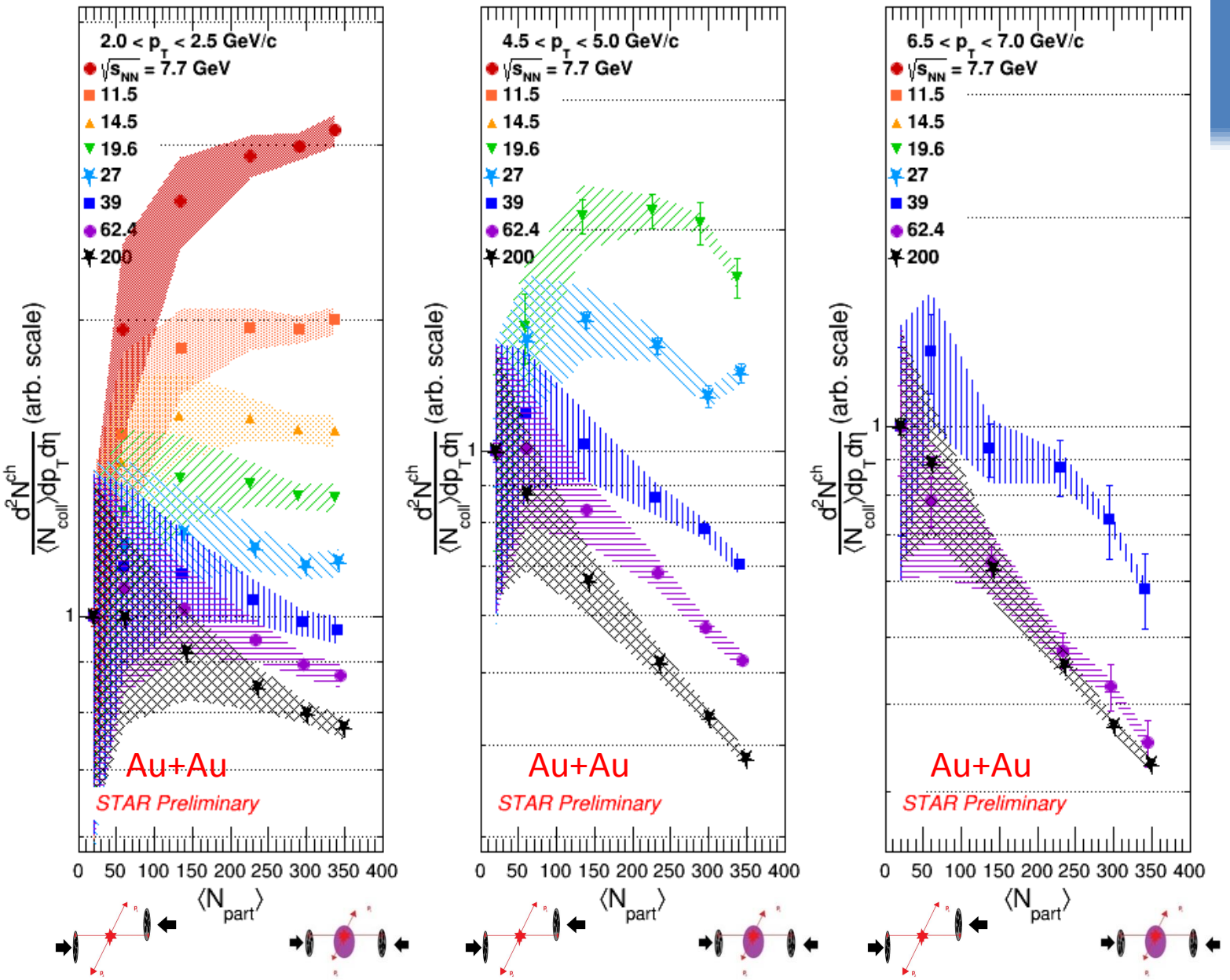




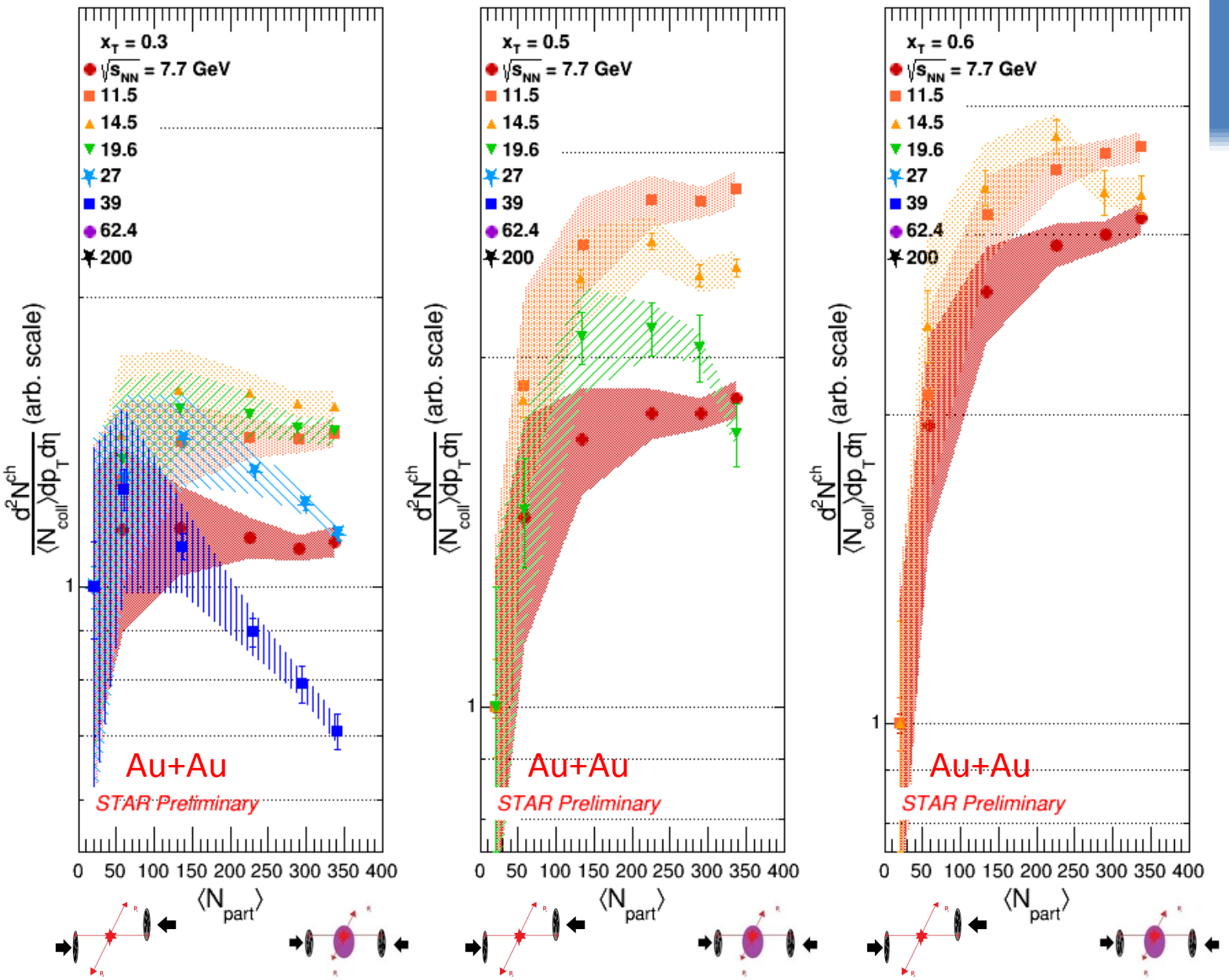
Thank you!



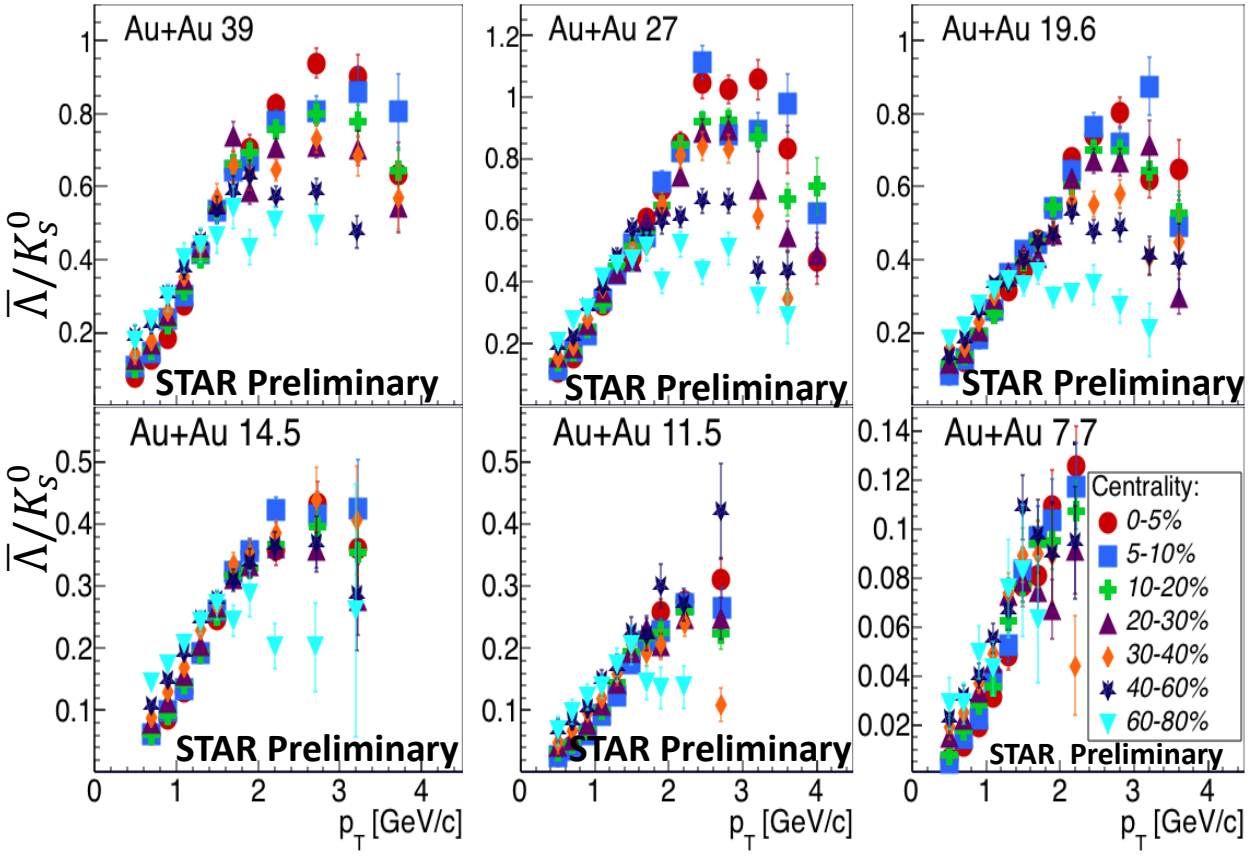
Backups


2.0 < p_T < 2.5 GeV/c
√s_NN = 7.7 GeV
11.5
14.5
19.6
27
39
62.4
200
Au+Au
STAR Preliminary
4.5 < p_T < 5.0 GeV/c
6.5 < p_T < 7.0 GeV/c
d²N^ch / ⟨N_coll⟩dp_T dη (arb. scale)
⟨N_part⟩
0 50 100 150 200 250 300 350 400

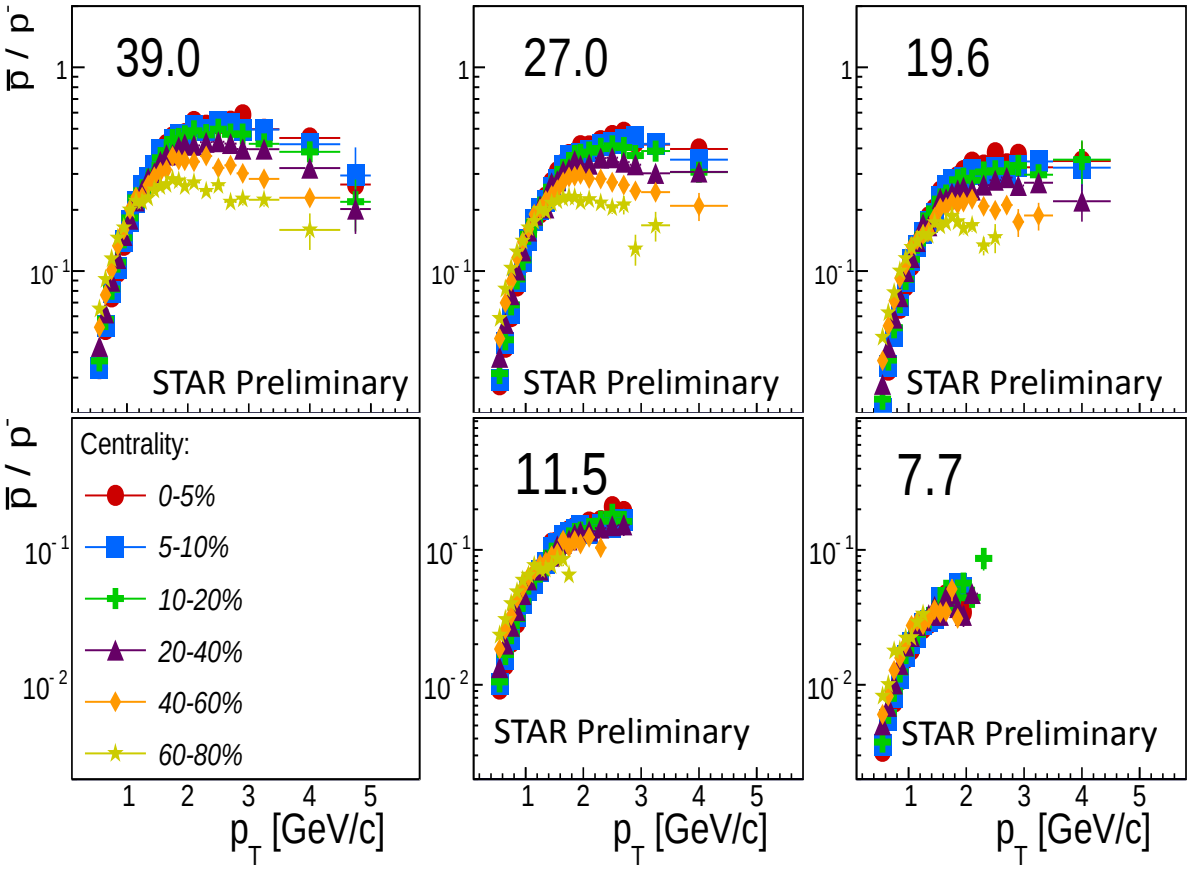
x_T


x_T = 0.3
$\sqrt{s_{NN}}$ = 7.7 GeV
11.5
14.5
19.6
27
39
62.4
200
$\frac{d^2N^{ch}}{\langle N_{coll}\rangle dp_T d\eta}$ (arb. scale)
Au+Au
STAR Preliminary
0 50 100 150 200 250 300 350 400
$\langle N_{part}\rangle$
x_T = 0.5
$\sqrt{s_{NN}}$ = 7.7 GeV
11.5
14.5
19.6
27
39
62.4
200
$\frac{d^2N^{ch}}{\langle N_{coll}\rangle dp_T d\eta}$ (arb. scale)
Au+Au
STAR Preliminary
0 50 100 150 200 250 300 350 400
$\langle N_{part}\rangle$
x_T = 0.6
$\sqrt{s_{NN}}$ = 7.7 GeV
11.5
14.5
19.6
27
39
62.4
200
$\frac{d^2N^{ch}}{\langle N_{coll}\rangle dp_T d\eta}$ (arb. scale)
Au+Au
STAR Preliminary
0 50 100 150 200 250 300 350 400
$\langle N_{part}\rangle$

Baryon/Meson Ratio : $\bar{\Lambda}/K_s^0$



Baryon/Meson Ratio p-bar/π^-



Coalescence vs Fragmentation

Quark (parton) coalescence

Coalescence

$$\frac{dN^r}{dp_T}(p_T) \sim C_r \times \left(\frac{dN^q}{dp_T}(p_T/n)\right)^n$$

Hadrons from coalescence have larger momentum than the quark momentum

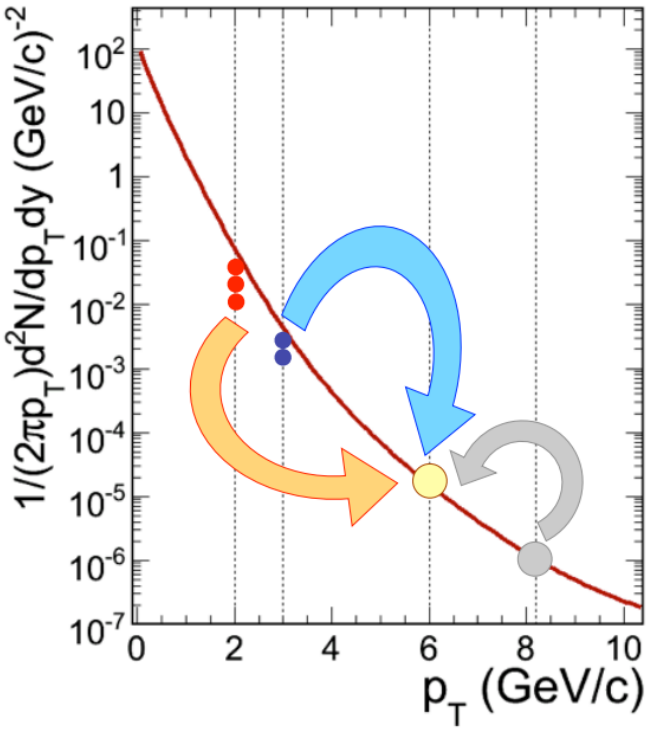
$$p_T^h > p_T^q$$

Fragmentation

$$\frac{dN^f}{dp_T}(p_T) \sim \frac{dN^q}{dp_T}(p_T/z)(z<1)$$

Carry only a fraction (z < 1) of the initial quark momentum

$$p_T^h < p_T^q$$



*D. Molnar and S. A. Voloshin, **PRL91**, 092301 (2003), R. C. Hwa and C. B. Yang, **PRC66**, 025205 (2002), V. Greco et al, **PRL90**, 202302 (2003), R. J. Fries et al, **PRL90**, 202303 (2003), ...*

$$v_2^h(p_T) \approx n_q v_2^q(p_T/n_q)$$

- Hadron productions by quark coalescence picture
- Specific scaling pattern for meson and baryon v_2

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